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FINAL REPORT

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M-R-C RESEARCH PROPOSAL NO. 1382

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

Method of Producing Improved Bearing Components
by Elimination or Control of Fiber Orientation

(NASA Contract NASw-72)

November 15, 1963

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NOTICE

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ABSTRACT: Over the past three years, research has been conducted on SAE 52100 and AISI M-50 steel balls. The initial intent of this testing, was to improve fatigue life of balls by reducing or eliminating end fiber areas. The end fiber areas, in previous testing, (Ref. 1 and 2) have been shown to be more sensitive to spalling than areas where fiber is parallel to the surface.

Numerous lots of balls were manufactured by various methods or modifications of standard manufacturing methods. None of these methods produced balls in which end fiber areas were significantly reduced.

Tests of balls produced by various methods of manufacture, intended to reduce end fiber areas, gave varying results This indicated the importance of other variables which require control before the effects of end fiber can be completely analyzed. Additional experimentation was directed to an evaluation of the effect of non-metallic inclusions, rate and magnitude of plastic deformation in material processing as well as continued fiber orientation studies.

Three lots of balls have shown a significant improvement in fatigue life. One lot, peened at room temperature in the pre-hardened condition, showed a significant reduction in life scatter. A second lot, manufactured for purposes of obtaining high silicate non-metallic inclusions, showed a significant reduction in the frequency of spalling of end fiber areas accompanied by exceptional average fatigue life of normal scatter. The third lot, containing high aluminate non-metallic inclusions, showed a significant improvement in the fatigue life of end fiber material.

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INTRODUCTION: A research program to investigate the effect of fiber orientation on rolling contact fatigue life was one of the projects carried on by the Subcommittee on Lubrication and Wear, originally under the National Advisory Committee for Aeronautics and reconstituted under the National Aeronautics and Space Administration. Data produced by NASA Lewis Research Center, has shown that end-grain or fiber demonstrates high sensitivity to failure by spalling. This conclusion is based on correlation of frequency of spalls ocurring in end and side fiber areas with the anticipated frequency based on position of ball track with respect to fiber areas.

On the basis of these data it was proposed that MRC conduct a Research Program to reduce or eliminate the end fiber areas of bearing components. Work includes the fabrication of test specimens (balls) in which fiber orientation variables are controlled and the testing of these specimens in NASA type five ball test rigs. In the initial phase, six different types of ball fabrication were evaluated including the present conventional method, a pinch-off method, a twist-off method, cross extruded metal powder rod, peened balls, and balls fabricated by conventional methods from rods with the grain flow normal to the usual axial grain flow.

Preliminary results of this initial phase tended to confirm the theory that the effect of material fiber orientation was a manifestation of more fundamental material characteristics. Results indicated that percent reduction or degree of working on the structure of material affects rolling contact fatigue life. It was also hypothesized that impurities or inclusions in the steel would effect, in varying degree, the resistance of end and side grain material to failure in rolling contact fatigue. Consequently the program was expanded to include a study of the effects of explosive hardening, percent reduction in drawing material into ball wire, peening of balls before and after heat treatment, ausforming, and a study of effects of non-metallic inclusions.

Work conducted under M-R-C Research Proposal No. 1298 wherein balls were tested at NASA Lewis Research Laboratories is referred to herein as Phase I. Work conducted under M-R-C Research Proposal No. 1382 wherein balls were tested on similar rigs at M-R-C Research Laboratories is herein referred to as Phase II. All work was conducted under Contract No. NASw-72. The procedures, results and conclusions of the entire program under this contract are reported.

PROCEDURE: Test Specimen Fabrication:

<u>Phase I</u>

300 lbs of SAE 52100 induction vacuum melted steel rod was centerless ground for ball fabrication in Phase I. Lots DK, DN, DM, and EB were obtained from this heat of material. Characteristics of this heat are shown in Table 1.

The following lots of balls were fabricated for testing in this program:

<u>LOTS DK and DN</u> (Reference Balls)

Two lots of reference balls were manufactured by conventional methods: Lot DK hardened and tempered to Rockwell C 64, and Lot DN hardened and tempered to Rockwell C 58. The second lot, Rockwell C 58, was necessary for comparison with Lot DM which was the same hardness.

LOT DM (Pinch-Off and Twist-Off)

A four stage die, later extended to six stages, was used to forge a ball from bar stock. The first five stages formed an egg-shaped specimen with progressively smaller ends. In the pinch-off method, the ends are then sheared and a rough ball formed in the final round die cavity. The intended method of fabrication for a twist-off group was not successful, due to inability to control slug size, preliminary to the final forming operation.

LOT DL (Sintered)

This lot was fabricated from SAE 52100 metal powder which was compacted, sintered, and cross extruded into rod. The rods were then sectioned into slugs and hot headed into ball forgings. Due to the lack of ductility in sintered material cold heading of the cross extruded rods was not possible utilizing conventional equipment and methods.

LOT EB (Peened)

Balls stabilized at 1200°F were automatically removed from the furnace to the peening tube where they were hit by an air actuated piston. After being driven against a hardened steel plate, balls were automatically returned to the furnace to maintain temperature. Approximately 40 balls composed a peening load, and peening was continued for 24 hours for the full load. Balls were 0.506" in diameter prior to peening, heat treatment, and final finishing to test diameter. The peened balls were finished to 0.490" diameter, erroneously. Tests results have been corrected for the difference in stress resulting from this small diameter.

Phase II

Nine different heats of material were utilized in Phase II as follows:

I A heat of SAE 52100, vacuum induction melted, and centerless ground into 0.375" diameter ball wire was conventionally formed into 0.52" diameter ball forgings from which lots 5, 7, 8, 10 and 11 were finished.

II Three heats of SAE 52100, vacuum induction melted, were cast to a range of ingot sizes which were drawn directly into ball wire, eliminating the billet stage, to give a known percent reduction in cross sectional area. Rods were centerless ground to 0.375" diameter from which ball forgings were conventionally formed. This material was used in the fabrication of 18A, 19A, 22A, and 22B.

III Three vacuum induction melted heats of SAE 52100 had inclusions (sulfides, aluminates, and silicates) added to the melts to obtain JK* ratings of 4-5. Lots 24, 25, and 26 were obtained from this material.

IV A heat of consumable electrode melted M-50 material was obtained for fabrication into lots 1 and 27. Due to fabrication difficulties of Lot 27, it was necessary to utilize a second heat

LOTS 1 and 8 (Reference Balls)

Lots 1 and 8, made from AISI M-50 steel and SAE 52100 steel respectively, are reference lots manufactured by conventional methods.

LOTS LO and TV

Two lots of balls were fabricated from 1/2" cross rolled plate, AISI M-50 material. 1/2" square bars were cut from the plate in the longitudinal and transverse directions and ball wire was turned and centerless ground from the bars. This series of operations yielded ball wire with controlled fiber orientation. In one lot, the fiber orientation was parallel to the ball wire axis. In the other lot, the fiber orientation was perpendicular to the ball wire axis (Fig. 1). Ball wire was then cut to appropriate slug length, cold headed, and finished in the conventional manner.

LOTS 5 and 7 (Explosive Hardened Group)

SAE 52100 balls were formed conventionally and rough ground to 0.520". A separate investigation was initiated in cooperation with the Rocketdyne Division of North American Aviation to study the feasibility of explosive treatment on SAE 52100 steel balls. It was originally agreed that Rocketdyne would design shaped charges and initiators that would create a 100 Kilobar (minimum) implosion on the rough ground, 0.520" diameter balls. The original design, as well as design modifications at this implosion level failed to produce samples free of macro or micro-cracks. A reduction of the implosion force to 50 Kilobars resulted in satisfactory performance Fifty balls each of Lots 5 and 7 were treated at this implosion level using

Dupont sheet explosive EL-506A and Rocketdyne plastic PVC-3 and PVC-4 as shock transfer media. Lot #5 was hardened and tempered to Rockwell C 60 before explosive treatment. Lot #7 was hardened and annealed to Rockwell C 15, explosively treated, and rehardened and tempered to Rockwell C 62. Both lots were then finished in the conventional manner.

LOTS 18A, 19A, 22A and 22B (Reduction Group)

Within this group, are lots processed from different heats of material. This variable is unavoidable, due to the nature of the manufacturing process. The lots were processed by pouring various size ingots. The ingots, inturn, were swaged and drawn to the appropriate size of ball wire. The difference in cross sectional area between the ingot and ball wire is expressed in percentage reduction of cross sectional area.

LOT	REDUCTION
18A	40%
19A	60%
22A	90%
22B	75%

Balls were then processed from ball wire in the conventional manner.

LOTS 10 and 11 (peened - Room Temperature and 900°F)

Balls were conventionally formed and rough ground to 0.520" diameter. Lot 10 was hardened and tempered to Rockwell C62, then peened at room temperature. Lot 11 was peened at 900°F in the spherodized annealed state, then hardened and tempered to Rockwell C62.

Peening was done in a single ball, five tube, ball-peening rig. This equipment was designed and built for this work. Design is shown on M-R-C Research Drawing #R-51618-B. The equipment was operated at 40 cpm for 3 hours treatment on each of five balls. The rig is powered by air pressure which is variable in order to control the amount of deformation in balls of differing temperatures. Lot 10, hardened and peened at room temperature, was processed with 30 psi air pressure to the drive piston, and a resulting surface deformation of approximately .002" to .003" per surface. The same pressure on annealed material at 900°F (Lot 11) resulted in deformation in excess of .010" per surface or .020" per diameter. Drive piston pressure was reduced to 10 psi resulting in a surface deformation of .004" to .005" for Lot 11.

LOT 24, 25, and 26 (Non-metallic Inclusion Group)

Again, because of the variation within the group, it was necessary to process a different heat of material for each lot. Therefore, these lots have no control or reference group. In each heat of material, excessive amounts of sulfur, silicon or aluminum respectively, were included to produce ball material which would have an inclusion content of 4-5 JK* -- inclusions types A, B, or C. Each lot is the product of one 50 lb laboratory heat produced by the Syracuse Research Laboratory of Crucible Steel Company of America, under the following heat number and chemical analysis:

	LOT #24 High Sulfides Heat #090817	LOT #25 High Silicates Heat #090819	LOT #26 High Aluminates Heat #090816
C	1.06	1.06	1.07
Mn	.138	.27	.37
P	.002	.002	.002
S	.022	.005	.005
Si	.27	.35	.26
Ni	.02	.03	.03

The chemical analysis and non-metallic inclusion ratings constitute the variables within this group. Balls were manufactured in the conventional manner.

LOT 27 (Ausformed Material)

It was first attempted to form AISI M-50 balls in the ausformed condition by austenitizing the normal size ball slug and stabilizing at 1000°F immediately prior to the forming operation. Balls were oil quenched immediately after forming. Because heat treatment was done in small laboratory furnaces, which could not incorporate a controlled atmosphere, a rather severe decarburization and scale build-up resulted on slugs and formed balls. The forming operation also met with difficulty. Individual handling of each slug when placing it in the die cavity introduced unavoidable inaccuracies of slug alignment which were amplified by the vibration caused by ram motion. This caused an irregular flash at the equator and voids in the sphere. The majority of the rough formed balls were sufficiently irregular to prohibit finishing to 0.500" diameter.

The acceptable approach was to ausform a solid bar by austenizing and forging a 50% (minimum) reduction between the temperature of 1200°F and 600°F. Balls were then ground directly from the ausformed bar stock without any additional working or heat treatment.

Test Rig Description

Tests of lots DK, DN, DM, DL, and EB were conducted at NASA Lewis Research Center. Tests of subsequent lots were conducted at M-R-C Research Laboratories. The MRC rigs are essentially the same as those designed by NASA, Lewis Research Center. (See Ref. 4 and MRC Drawing #R51653-B). The rig is a modified drill press which has been adapted for ball testing. The basic rig is sufficiently versatile that it may be operated at any desired speed and load, and also be used for high temperature work. The specimen holder portion of the rig has been adapted to ball testing using three or four support balls with one test ball which may operate at any contact angle between 10 and 40 degrees. The specimen holder area may also be adapted to accept a test bearing operating under thrust load. In both ball and bearing testing, the speed and load are variable.

High temperature work may be accomplished by the use of a heat jacket which surrounds the specimen holding area. Cartridge type heaters incorporated in the heat jacket allow variable testing temperatures between room temperature and 700°F. Each rig is separately driven by a three-quarter horsepower, 3,450 rpm motor with positive drive, pulleys and belts. The loading mechanism is a lever-action dead weight type, acting on the drill press spindle.

Since it is important to determine the initial incidence of fatigue spalling, both to determine cycles of operation and cause and location of failure, much effort was directed to automatic shut-off methods. Use of structure borne vibration to trigger shut-off was generally unsatisfactory. The presently used system has been found to be most reliable and is described as follows:

A maximum of five amplifiers are powered by an externally regulated power supply. The output of a crystal microphone is fed through an attenuator into a two-stage amplifier. The signal then proceeds to a band pass filter which is composed of active elements. This filter passes only the critical frequency range. The output of the filter is amplified in a power tube which in turn actuates a thyratron tube. The output of the thyratron tube actuates a circuit breaker relay which interrupts the power to the drive motor.

Test Machine Operation

All tests were conducted under the following conditions:

Speed	- Test ball and drive spindle - 10,650 rpm (532 stress cycles per second)
Contact Angle	- 30°
Load	- 800,000 psi maximum Hertz Stress
Test Temperature	- Ambient
Outer Race Temperature	- Phase I - 140° - 155°F Phase II - 110° - 135°F
Lubricant	- MIL-L-7808
Lubricant Flow Rate	- 8-8.5 gm/hr

Lubricant is introduced to the test specimen area through a capillary tube, assisted by air pressure which can be regulated to control flow rate. Lubricant flow was varied, between 10 grams per hour, and 4.5 grams per hour. No significant difference was noted in fatigue life due to the amount of lubricant used, and therefore, it was determined to standardize on 8 to 8.5 grams per hour of lubricant flow.

Test Rig Correlation:

The tests conducted under Phase I of this program were run at Lewis Research Center, NASA. The tests conducted under Phase II were run at MRC Research. A correlation therefore became necessary between the two sets of rigs. The first test was conducted on Lot DN by MRC Research in an effort to correlate with testing of the same lot run at Lewis Research Center, Phase I. (Graph 1)

TEST RIG	TEST BALL	B-10	B-50
NASA	Lot DN	5.8	170
MRC	Lot DN	17.5	76.5

Although the correlation between NASA rigs and MRC rigs was acceptable for SAE 52100 material, additional correlation testing with AISI M-50 material was recommended by NASA personnel. The test conditions were duplicated as closely as possible, in that the M-50 test balls, 52100 slave balls, and Turbo 15 (MIL-L-7808) oil were all furnished by NASA. (Lot A Table II, Graph 2).

Because of the vast difference in fatigue life between the NASA and Lot A of the MRC tests the lubricant flow rate was suspected. Lot B was tested with an increased lubricant flow rate. The results of this test were lower than Lot A which inturn led to suspicion of lubricant quality. Lot C was tested using a new supply of Esso Turbo 15 oil (MIL-L-7808). The results of this test were within the limits of reliability of the original NASA test. It was therefore determined to be a reasonable correlation.

One additional test was conducted to compare the fresh 7808 oil with Mineral oil (WS-4138). (Lot D Table II, Graph 2) This lot also showed reasonable correlation with Lot C and the NASA test lot. It was therefore determined that continuation of testing with fresh MIL-L-7808 would be satisfactory although the more stable characteristics of mineral oil should be considered for future work.

Evaluation: Mean and Median

In normal statistical distributions, the terms "mean" and "median" define methods of arriving at a single value as being a reliable measure of a group of values.

The "mean," more commonly referred to as the average, is determined from the total of single values divided by the number of values, the median is the value corresponding to 1/2 the range of single values when single values are arranged in ascending order. The mean is slightly more affected by extreme values than the median. The near-equality of the two values is therefore an indication of the absence of extreme values and symmetry of the frequency distribution. (Ref. 8).

Corrected End Grain

Lines labled "Corrected End Grain" on Weibull Graphs, Series B, are included for reference.

As noted in the appendix of this report, a point of contention exists relative to the validity of corrections for stressed volume. The report is discussed from the point of view that the correction is not valid. To accept the validity of the stressed volume correction factor does not significantly change the results of this report because the limits of 90% reliability for sample sizes tested are sufficiently wide to include corrected and uncorrected plot distributions.

RESULTS:

Extent of Fiber Orientation Studies

Successful fiber orientation studies were conducted on a majority of lots from this investigation. The results and conclusions of these studies are included in this report.

The procedures used to conduct fiber orientation studies were as follows:

Each failed test ball was macro etched in either "commercial" or "reagent" grade concentrated hydrochloric acid at 230°F (110°C) for 5-10 minutes. After an alcohol rinse and warm air dry, the location of failure was noted in relation to its occurrence on end or side fiber. During this study a number of failures were observed to occur at the extreme edge of the pole area extending into the side fiber area. For purposes of this study, these failures were considered to be end fiber failures because it is believed that these failures are influenced by the close proximity or presence of end fiber material.

It is suggested that further work be conducted which considers the extent of the incidence of failure at the end-side fiber intersection, such as the edge of the pole area and the equator.

Difficulty was experienced in completing fiber orientation studies in some lots due to material variables.

AISI M-50 tool steel exhibits an extremely fine structure. Due to this condition, the material does not show fiber orientation with any significant degree of clarity in the macro etched condition. For this reason, lots LO, TV, 1 and 27 are not included in fiber orientation studies.

The same condition was true of Lots 18A, 19A, and 22B; however for a different reason. As will be noted under the Results of the reduction group, the balls from 3 lots of this group did not clearly show fiber orientation following macro etch due to insufficient chemical segregation; which, inturn, was due to rapid cooling of the small ingot.

PHASE I

Five lots of balls were fatigue tested during this Phase. These lots consisted of:

Lot DK (Reference Balls Rc 64) - Graph 5, 6, 7; Table III
Lot DN (Reference Balls Rc 58) - Graph 5, 8, 9; Table IV
Lot DM (Pinch-Off) - Graph 4, 10, 11; Table V
Lot DL (Sintered)
Lot EB (Peened at 1200°F) - Table VI

LOT DL

This lot suffered extremely early catastrophic failure. The average ball life was 0.10 hours, compared to average lives in excess of 25 hours for all other lots. No further consideration has been given to this material. The fatigue life of the lot is not included in the

Composit Weibull Plot (Graph 39) nor is it included in failure probability studies of fatigue life - fiber orientation studies. Other testing at MRC Research has also resulted in extremely low life from cast 52100 material.

LOT DM (Pinch-Off)

The fatigue life of this lot was generally low (B-10 3.2*) when compared to its reference lot. The comparison as shown in Weibull Graph 4, is somewhat exaggerated due to a two point variation in hardness between individual balls of the reference lot. This is probably the reason for the excessive scatter shown in lot DN (Slope 0.55). Another test of the same lot conducted for purposes of correlation of Phase I with Phase II showed a more reasonable fatigue life distribution (B-10 17.5*- Slope 1.35).

When this lot was etched, the end fiber areas were not shown with any great degree of certainty, and the tabulation of the location of spalls is at best, a calculated guess. Sufficient clarity was shown however, to conclude that the areas of end fiber material had not been reduced to any significant degree by this method of manufacture.

LOT EB (peened)

This was the only lot in this Phase which showed superior fatigue life when compared to its specific reference lot. Later in the program, two additional lots of peened balls were tested. Lot EB is included in the discussion of results of testing these balls.

*Fatigue Life - Stress Cycles X 10^6

PHASE II

LOTS LO and TV

These lots were manufactured from longitudinal and transverse sections of cross-roll M-50 plate. Comparison of these lots indicates that there is no significant difference in the fatigue life of balls manufactured by these two methods. (Graph 12) It is unfortunate that M-50 was chosen for this portion of the investigation, due to the difficulty in determining the surface fiber orientation in the finished ball. If we trace the fiber orientation through the manufacturing process, we can estimate that Lot LO had approximately 38% end fiber and that Lot TV had approximately 62% end fiber, (Fig. 1). If this relationship of end and side surface fiber could be proven, results of these tests would give further support to the theory set forth in the appendix of this report; that fatigue life of end and side fiber material is independent of the "stressed volume."

It is therefore, suggested that this ball manufacturing method be included in any further work on fiber orientation studies in balls.

Slave Ball Hardness

During the testing of Lot TV, another significant difference in fatigue life was shown to be caused by a variation in hardness of support balls. During this testing, the supply of support balls was depleted and it was necessary to acquire a new group of support balls. Shortly after the new support balls were in test, it became apparent that the life of the test balls had been drastically reduced. A subsequent check to determine the cause of this reduction in life was completed, utilizing M-50 support balls and 52100 support balls with hardness about 2 points Rockwell C higher than the original M-1 balls. The results of this testing are shown below and indicate that the hardness of the support balls relative to the test specimen is vitally important.

TEST SPECIMENS		LIFE		SUPPORT BALLS	
Material	Hardness Rc	B-10* Revs	B-50* Revs	Material	Hardness Rc
M-50 (Transverse)	62.3	36.0	269.0	M-1	62.1
M-50 (Transverse)	62.3	7.4	71.0	M-50	64.2
M-50 (Transverse)	62.3	8.8	77.0	52100	64.1

This phenomena is demonstrated graphically in Graph 3.

It has been shown in this and other reports, that test ball hardness has a marked influence of life. The above has shown that the slave ball hardness also has a marked influence on life. This information suggests that we can no longer depend on a graph of dynamic capacity as a function of hardness. Since the hardness of each of the elements composing a rolling contact fatigue test area affect the results, we would then expect that optimum life of a system will be realized from optimum hardness in each member of the system as well as optimum hardness relationship between the members of the system.

Regardless of optimum life, the hardness of each system member and the hardness relationship must be considered variables in 4- or 5-ball testing and so controlled to yield the desired results.

*Fatigue Life - Stress Cycles 10^6

Questions raised by these results became the basis for a separate investigation. Balls having several different hardness levels were supplied to NASA Lewis Research Laboratories for test. Results of this testing are not included herein but will be the subject of a separate report.

Explosive Hardened Group

This group included Lot 5 explosively treated at Rc 60 and Lot 7 explosively treated at Rc 15. Both of these lots exhibited inferior fatigue life (Graph 13, 14; Table VII).

It is suspected that explosive treatment has introduced residual tensile stresses in the surface of these balls. The following evidence supports this contention. A number of balls from Lot 5 exhibited cracks in the side grain material after testing. The cracks were shown running parallel to the wear track after balls were macro etched in hot concentrated hydrochloric acid. Residual stresses are additive to stresses introduced by rolling contact, the sum of these being sufficient to cause failure by cracking(Ref.9). It will also be noted from Graph 15 of the Explosive Hardened Group that Lot 5, exploded after hardening exhibited increased scatter over Lot 7, exploded in the soft condition, and the reference lot from the same heat of material. If the scatter of values of fatigue life is due to randomly oriented stress risers in the material, then the effects of a residual tensile stress on the surface of a ball would amplify this scatter by introducing a stress pattern which is favorable to crack propagation initiated by such stress risers. Since Lot 7 was explosively treated in a soft condition and subsequently heat treated, any unfavorable residual stress patterns imparted to the surface of the ball by explosive treatment would be reduced by any insuing heat treatment.

The study of the end and side fiber failures Lot 5 indicates that the Weibull Plot is a poor choice of statistical method for the evaluation of this type of information. The Weibull Plot places emphasis on low life failures. The lower half of the graph is used to plot the first 20% of the failures, Great emphasis is placed on the B-10 life in the bearing industry because of the need for reliability. This emphasis is justifiable when considering critical bearing applications. However, when the use of the plot is extended to areas of more basic research, such as the investigation of material properties and failure mechanisms, it introduces the danger of drawing false conclusions. This danger is removed when a more basic statistical approach, such as the bar chart, step chart, or normal frequency curve, is employed.

Consideration of the side fiber failures of Lot 5, demonstrates the above condition. Weibull Plot Graph 16 shows that the side fiber areas of this lot are decidedly superior in fatigue life. When the same data is evaluated by means of a step chart (Graph 17, Table VIII) we find that the superiority of side fiber material is an erroneous conclusion. While the first three failures in side fiber material showed a decided improvement in fatigue life over the first three end fiber failures, the improvement is not proportional throughout the range of values. Four failures occurred between 19.3 and 20.0 hours. Beyond this point, failures were 100% preferential to the end fiber material. This is understandable when we consider that the preferential tendency can be of very low magnitude and still be sufficient to cause a predominance of failure in one area.

If we again accept the theory of a random distribution of stress risers in respect to distance from the surface and that the affect of these stress risers is amplified by a residual tensile stress and that the tensile stress has a greater preferential effect on end fiber material, (analogous to the difference in tensile strength and ductility of cold rolled sheet material in the longitudinal and transverse direction) we have a set of conditions which explains the results.

Consideration of both step chart (Graph 18) and Weibull Graph 19, (Table IX) of Lot 7 shows that there is very little difference in fatigue life in the end and side fiber material. The frequency distribution of failure (Table XIII), is more favorable, with a 40% end fiber frequency and 60% side fiber frequency, which is approaching the desired theoretical probability. This change in failure frequency and life distribution can only be due to the effect of heat treatment following the explosive treatment. As previously noted, the unfavorable residual stress patterns are reduced in magnitude by the heat treatment. The ball, therefore, shows more of the residual stress characteristics imparted by the heat treatment and less residual stress characteristics remaining from the explosive operation.

Reduction Group

This group is composed of Lots 18A, 19A, 22A, and 22B (Graph 20).

The method of fabrication, used to produce these definite percentages of reduction, has certain inherent disadvantages. Various small sizes of ingots were poured and ball wire drawn directly from the ingot. The rapid cooling of the outer surface of the small ingot traps gases inside, similar to the condition experienced in chill casting. When ball wire is drawn from the porous ingot, the trapped gas pockets are greatly elongated. The condition is still present when a ball is formed. The defects are subsequently disguised by smearing in the high speed finishing operation. The defects, therefore, are present immediately below the surface of the finished ball and are revealed by the etching reagents removing the smeared surface.

TABULATION OF POROSITY, FIBER ORIENTATION AND LIFE

Lot #	Reduction %	Porosity	Evidence of Fiber Orientation	B-10	B-50
18A	40	Little	None	16.5	58.0
19A	60	Excessive	None	4.3	15.5
22B	75	Varying degrees	Some pole-no equator	8.0	44.0
22A	90	Scattered	Good Poles	15.5	60.0

A correlation is observed between life of the different lots of reduction and the degree of porosity exhibited as a result of macro etching as will be noted from the preceding tabulation. Lot 19A showing the poorest life, also shows excessive porosity. Lots 18A and 22A, in comparison, show very little porosity and good life when compared to the rest of the reduction group. The word 'scattered' under porosity for Lot 22A refers to scattered evidence of porosity within the lot. It was also noted in cases where porosity was evident, it was rather severe.

Lot 22B exhibited various degrees of porosity within the lot, ranging from 'very little' to 'medium' in severity. This could very well be the reason for increased scatter in this lot.

The intention of investigating this group was originally to show the affects of material working on fatigue life. Due to conditions outlined above, testing has shown the affects of porosity on fatigue life. These results are sufficiently evident to overshadow any evidence of correlation of the degree of material working with fatigue life.

It is also interesting to note from the same tabulation, the correlation between percentage reduction and evidence of fiber orientation. The lower percentages of reduction were made from smaller ingots. The smaller the ingot, the more rapid the cooling, and therefore, less time is allowed for grain boundary constituents to precipitate to the grain boundaries to be attacked by the etching reagent and subsequently show grain-fiber orientation. Due to this situation it was possible only in Lot 22A to analyze failures in end and side fibers. We notice from Weibull Chart (Graph 21, Table X) and the step graph (Graph 22) of this lot that again there is very little difference in the fatigue life of end and side fiber material. Similar results are evident in reference lots of 52100 balls, and we would have no reason to suspect otherwise; since standard ball material is worked in excess of 90% in the billet stage.

Peened Group

Lots 10, 11 and EB were peened at room temperature, 900° and 1200°F respectively. Micro-examination of a peened ball from Lot EB, prior to heat treatment, revealed an area penetrating approximately .0002" into the surface of the ball in which carbides appeared to be of a more uniform size and distribution. The depth of this observable penetration of the hot peening effect was, of course, removed during the finishing operation.

This same condition was also observed in Lots 10 (Graph 23, 24; Table XI) and 11 (Graph 25, 26; Table XII). In all three cases fatigue life has been improved by the peening treatment. The notable difference between the three lots is the scatter of results or the slope of the Weibull Plot (Graph 27). Lot EB had a slope of 0.87; Lot 11 had a slope of 1.76; and Lot 10 had a slope of 2.14 (it was erroneously reported in Quarterly Report No. 15 that the slope of Lot 10 was 3.73). It is thought that residual compressive stress imparted to the surface of the ball by the peening treatment is responsible for the varying degrees of scatter or slope noted here. Since Lot 10 was peened after heat treatment, it would therefore possess the greatest level of residual compressive stress in the finished form. In Lots 11 and EB, stresses imparted to the ball by the peening treatment are partially relieved by the presence of heat in the same treatment. Additional heat used in the hardening and tempering of these two lots also serve to reduce the favorable stress levels.

If we again accept the theory that normal scatter in the fatigue life of bearing components is caused by sub-surface stress risers, then a surface or immediately sub-surface residual compressive stress of any magnitude would counteract crack propagation initiated by sub-surface stress risers. It is then logical to assume that the greater the residual compressive stress in a particular lot the less the scatter to be exhibited Comparisons of end and side fiber material from the standpoint of failure probability, (Table XIII) and low life failure, (Graph 27), both indicate the superiority of room temperature peening. As the temperature of peening approaches room temperature, the relative number of end fiber failures decreases and the life increases. (Graph 28, 29).

This is in line with the theory expressed concerning end fiber failures of Lot 5 where residual tensile stress is believed to be responsible for the high frequency of end fiber failure, low life failures and high scatter. The same is true to a progressively lesser degree in Lot 7, 8, EB, 11 and 10.

The closeness of values of the mean and median of Lot 10 (Table XI) (Graph 24) suggests that, the distribution of life values is becoming more normal statistically which in turn suggests that one mode of failure is predominating and therefore the other mode or modes of failure have been reduced or eliminated.

Non-Metallic Inclusion Group

Lots 24, 25, and 26 - High Sulfides, Silicates and Aluminates (Graph 30). The results of testing of this group has yielded an interesting comparison.

LOT	B-10 LIFE*
24 - Sulfides	27.0
25 - Silicates	43.0
26 - Aluminates	6.7

Here we have results of fatigue testing of 52100 material where the variations between the lots is within the range of specifications of chemical analysis, however, all three lots would be rejected for standard bearing production on the grounds of a high non-metallic inclusion rating. The variation of fatigue life between the lots is more than 6 times. This definitely indicates that more work is needed in this area and that the results of such work could be of great value. The only correlation first evident between the three lots upon studying the failure probability (Table XIII) and fatigue life of end and side fiber material (Graph 31, 32, 33) is the evidence of low failure probability in end fiber and the Weibull Plots (Graph 34, 35, 36) of end fiber failures in all three cases, show slightly

*Stress Cycles X 10^6

superior life of the end fiber material. Examination of the fatigue life fiber orientation (Table XIV, XV, XVI), show a predominance of early life failures in side fiber areas. Again, because the Weibull chart displays predominate emphasis on low life failures, the side fiber material shows an exaggerated low life and therefore the end fibers appears to have better life by comparison. The mean and median values and step charts (Graph 31, 32, 33) of the same data show more radical relationships of life in separate areas. Lot 24 shows no significant difference in life of end and side fiber areas. Lots 25 and 26 show decidedly superior life of end fiber material.

Ausformed Material

In evaluating Lot 27, the B-10 life is 5.4×10^6 stress cycles, and the B-50 life is 30.0×10^6. The slope is 1.11. The results of this testing are exceptionally poor for M-50 material which generally shows better fatigue life than 52100. (Graph 37). A preliminary hardness check shows a relatively soft test ball. Visual inspection of the test balls shows a well-worn track which was formed in a relatively short period of time. The poor performance of this lot was originally suspected to have resulted from either or both of the following conditions. Due to the excessive time taken to incorporate the 50% minimum reduction in cross sectional area in the temperature range of the lower belly of the S curve (600° - 1200°F), Bainite was formed.

The resulting structure would then be one of worked Bainite rather than ausformed. It was also suspected that due to excessive time at temperature required for working of the material that a decarburized surface resulted.

Further investigation showed that neither of these conditions were present in the finished test ball. The comparative Weibull Chart for this lot shows the slope to be practically identical to the control lot of M-50 material. However, spot checks of the test ball hardness indicate that a full ausformed structure was never achieved in this particular lot of material. These balls exhibit a hardness in the range of Rc 57, and a true ausform structure should exhibit an apparent hardness in the range of Rc 68 to Rc 70. The difference in fatigue life can, therefore, be attributed to low test ball hardness.

CONCLUSIONS AND RECOMMENDATIONS:

Fatigue testing of balls in NASA type five ball test rigs has been conducted to determine affects of manufacturing variables on rolling contact fatigue life. Work was conducted in two phases. The initial phase concentrated on developing manufacturing procedures and processes that would minimize end fiber area. Subsequent testing was directed to evaluation of affects of non-metallic inclusions, and rate and magnitude of plastic deformation in material processing. Results of this work are summarized as follows:

1) In general, attempts to improve fatigue life by minimizing the relative amount of end fiber material by new manufacturing methods under Phase I were unsuccessful.

2) Balls treated by the peening process, showed a significant reduction of early life failures, thus demonstrating reduced scatter and increased average life. The beneficial affect may be due to residual compressive stress imparted by the peening process, rather than an alteration of fiber orientation as originally conceived. More detailed studies of the affects of variables in the peening process should be undertaken.

3) Significant effects on fatigue life resulted from the life testing of balls produced with slight variations in SAE 52100 chemical analysis. This testing was proposed to investigate differences in fatigue life due to excessive amounts of silicates, aluminates, and sulfides. Two of the three lots tested, containing excessive silicates and sulfides, showed fatigue life superior to that of any reference lot.

4) Attempts to improve fatigue life by an explosive hardening treatment were unsuccessful. The results of this testing suggest that the poor fatigue life of these balls is due to residual tensile stress imparted by the explosive treatment. This is contiguous to the concept that residual compressive stress is responsible for the improvements derived from peening treatment.

5) In balls manufactured by conventional methods, as demonstrated by reference lot testing, there is a tendency toward preferential failure of end fiber material. This tendency is not strong, because there is no significant difference between the fatigue lives of end and side fiber material. Consequently, efforts to change the relative amounts of end and side fiber appear to be of little value.

Additional investigation is needed in the following areas before significant and reliable conclusions can be drawn.

6) Testing of balls manufactured from AISI M-50 cross-rolled plate (Fig 1) suggests that the stressed volume correction factor is invalid. Due to difficulties experienced in macro-etching M-50 material, the above assumption could not be proven. Additional investigation, using SAE 52100 plate material, processed similarly, is suggested to prove or disprove this assumption.

7) Attempts to correlate the degree of material working, prior to the drawing of ball wire, with fatigue life were unsuccessful, due to varying degrees of porosity in the ingots. It is suggested that additional work be conducted, using sections of large, commercial, vacuum degassed ingots from which ball wire is swaged and drawn.

8) Two attempts were made to produce ausformed balls. Both attempts failed to produce acceptable balls exhibiting ausformed structure and properties. It is suggested that further work be conducted on AISI M-50 tubing of relatively thin wall, possibly utilizing a high energy rate forming process.

9) The hardness of support balls causes significant variation in the fatigue life of the test ball. This indicates that an optimum hardness exists for each component of a rolling contact fatigue system, as well as an optimum hardness relationship between components.

10) The condition of MIL-L-7808 oil causes variations in fatigue life. Storage conditions or moisture, absorbed from the atmosphere can cause partial break-down, forming the acid and alcohol from which the product is made. It is theorized that this break-down may be detrimental to fatigue life. Due to this condition, the more stable characteristics of mineral oil are recommended for future work.

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APPENDIX: There are two ways to evaluate balls for failure sensitivity in end fiber areas.

Consider the number of failures occurring in end fiber areas in relation to the areas of end fiber present. In balls manufactured by conventional methods, results of rolling contact fatigue testing show that the number of failures in end fiber material is higher than expected. When a ball is etched, areas of end fiber material can be seen and measured. In balls tested under this contract, the areas of end fiber material vary between 30 and 38%. For the sake of this discussion, we will consider all balls to be 35% end fiber and 65% side fiber.

Between 55 and 60% of ball failures occur in the 35% side fiber area. The probability of failure of a ball track is the number of chances for failure in a particular area or track length divided by the total number of chances for failure or the total track length. This probability will hereafter be termed "theoretical probability."

Any ball considered for testing in a five-ball test rig and randomly oriented in the test spindle without respect to fiber orientation has a higher theoretical probability of failure on the side fiber area, if the mechanism of failure is not in any way related to these areas. The theoretical probability of failure on the side fiber area is 0.65 and the theoretical probability of failure on the end fiber area is 0.35. The total probability of failure is 1.00.

When a group of samples have been tested, and examined for failure in end or side fiber areas, and correlated in terms of actual failure probability in each area, there is a marked difference between the actual and theoretical probabilities.

In the case of Lot 8, the actual probability of end fiber failure of one additional ball from this lot is 0.61, and the probability of failure in the side fiber area of this same ball is 0.39. This is practically a complete reversal of the theoretical probability picture, and indicates that the failure mechanism is related to end and side fiber material characteristics. This is the only conclusion that can be drawn on the basis of a probability study. We know only that end fiber material is more sensitive to failure than originally assumed from area distribution.

The second method used in order to evaluate the degree of sensitivity considers the fatigue life. Fatigue life may be expressed in hours, revolutions, or stress cycles of a particular test sample. Failure of the test sample is the appearance of a distinct surface irregularity or spall at any point on the test track. The only conclusion which can be drawn from these data is that the particular point of failure was the weakest point on the test track and that its weakness was inversely proportional to the number of hours or revolutions or stress cycles which caused it to fail. Any other point on the same test track may have lasted one minute longer or 200 hours longer - we don't know and, therefore, we can make no statement about the life of the unfailed portion of the track. If we again consider that a ball is randomly placed in the test spindle without regard to any fiber orientation and that in doing so, we have in effect tested the entire ball surface (this may be a large assumption when we consider a lot of only 30 balls). We arrive at the conclusion that the point of failure is representative of the weakest point on the ball. In a great many cases, side fiber failures occurred in a track which ran over side and end fiber, showing that, in these cases, the end fiber material was stronger than the side grain.

The accepted method of evaluating fatigue life of a bearing or bearing component is the Weibull Plot, which is a graphical representation of the log of stress cycles, time or revolutions, compared to the log log of reciprocal of the median rank of survival (in other words, the log log of the failure probability).

When this method is applied to the data of this contract, it shows that there is no significant difference in life of balls failed in the end and side fiber areas.

A question has been raised relative to the validly of conclusions based on such Weibull Plots*. It has been suggested that a correction be made for stressed volume because the length of track in end fiber material is smaller than the length of track in side fiber material

*(Ref. 5 and 6)

and, therefore, the theoretical probability of failure is less in the end fiber material. However, it has already been shown that the theoretical probability of failure varies markedly from the actual probability which in turn proves that the actual probability of specimen failure is not mutually independent from the theoretical probability, and therefore cannot be statistically treated as mutually independent where the product of the independent probabilities equals the probability that both events will happen simultaneously.

In support of this theory, let us now consider the form equation of the Weibull plot and the effect of a stress volume correction on the equation.

$$K \log L + C = \log \log F_p$$

$$CL^k = \log F_p$$

$$\frac{.35}{.65} \times CL^k = \frac{.35}{.65} \times \log F_p$$

$$\frac{.35}{.65} \times CL^k = \log F_p^{\frac{.35}{.65}}$$

where K = a constant representing the slope

C = a constant representing the probability intercept.

L = Life expressed in stress cycles, hours, or revolutions

F_p = the failure probability or $\frac{1}{1-F}$

Notice that the application of the stressed volume correction factor exponentially to the failure probability equals the identical factor applied algebraically to the fatigue life.

To apply a correction factor which represents the theoretical failure probability to either the life or the failure probability is invalid. Since the theoretical probability differs from the actual probability, the theoretical probability cannot be mutually independent of the failure probability and therefore cannot be treated as such.

The life of an automobile tire is usually measured in miles; but a tire larger in circumference will have a greater life than a small circumference tire. Why? Only because the smaller tire has had a greater number of stress cycles on every point of its tread surface for every mile of road travel. Therefore, mileage is an invalid measure of tire life. "Stress cycles" or "revolutions" is a valid measure of tire life. A tire of circumference 0.35 C is analogous to the ball with 35% end fiber material. A tire of circumference 0.65 C is analogous to a ball with 65% side fiber material. A still larger tire with a circumference of C is analogous to the total surface of total track length of the same ball. The "stressed volume" of the 0.35 C tire is proportional to the "stressed volume" of the 35% end fiber material ball. 0.65 C is proportional to 65%, etc.

The life of the 0.35 C tire will be 0.35 L when L is measured in miles, and the life of 0.65 C will be 0.65 L, etc. But when life is measured in stress cycles, the lives of both or all three tires will be equal considering of course that other factors affecting life are equal - magnitude of each stress cycle, speed, etc. The same is true of a ball.

If the life of the end fiber material is measured in total distance travelled in end fiber, or the total number of stress cycles imposed on a particular area, prior to failure at some point, and the side fiber failures are treated similarly, then the life of each area expressed in this way would contain factors which express life in terms of a function of area. This is not a legitimate expression of ball fatigue life for the same reason that it is not a legitimate expression of automobile tire life; because the areas, track length and "stressed volume" are different.

As an alternative, we may measure fatigue life in stress cycles. Since every point on the track received an equal number of stress cycles, and one point on the track failed as a result of repeated stress, the fatigue life of that spot has therefore, determined the fatigue life of the track without regard to difference in area of end and side fiber. The information in this form will yield the desired answer.

We are investigating end and side fiber materials. And we wish to evaluate fatigue strength of this material. In order to do this, we must eliminate all other variables to the best of our ability. Area of end and side fiber is one of these variables, as are speed, load, hardness, chemical analysis, etc. The attached report will be discussed from this point of view. The validity of the point of view may be questioned; however, the extent of investigation required to prove or disprove the point is too great to be considered further under this contract.

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**Step Chart

GRAPHS

*Weibull Chart

**Step Chart

GRAPHS

*Weibull Chart

**Step Chart

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FINAL REPORT

M-R-C RESEARCH PROPOSAL NO. 1382

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

Method of Producing Improved Bearing Components by Elimination or Control of Fiber Orientation

NASA Contract NASw-72

November 15, 1963

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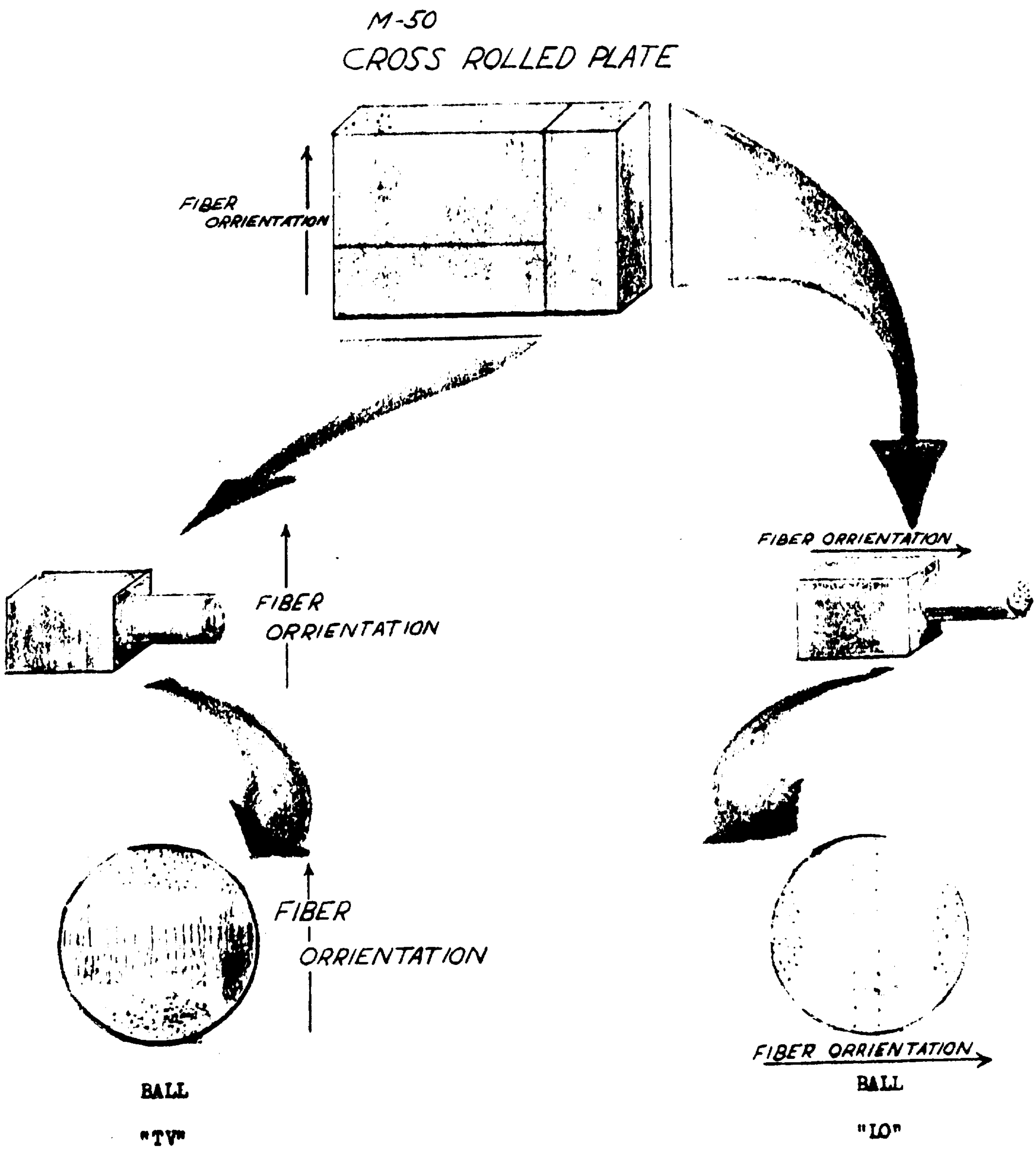
M-50
CROSS ROLLED PLATE
FIBER ORRIENTATION
FIBER ORRIENTATION
FIBER ORRIENTATION
FIBER ORRIENTATION
FIBER ORRIENTATION
BALL
"TV"
BALL
"LO"

TABLE I
RAW MATERIAL INSPECTION - PHASE I
INDUCTION VACUUM MELTED - 52100

Heat No. 00250

Analysis:

C	Si	Mn	S	P	Cr	Mo	Cu	Ni
1.10	.28	.34	.006	.007	1.48	.01	.02	.02

Non-Metallic Inspection:

	A	B	C	D
Top	1.0	1.0	0	1.0
Top	1.0	1.0	0	1.0
Bottom	1.0	1.0	0	1.0

All thin Series

Hardenability: Rc 64/65

Acid Test: Satisfactory

Fracture Inspection: Satisfactory

Magnaflux:

Step-Down Test

	No. Indications	Total Length of Indications
Top	0	0
Bottom	0	0

Carbide Distribution: Satisfactory

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TABLE II

TEST RIG CORRELATION

LOT	TEST RIG	TEST BALL	SLAVE BALL	LUBRICANT TYPE	LUBRICANT FLOW RATE	B-10	B-50
	NASA	M-50	52100	Turbo 15 (7808)	4.5 gm/hr	22.6	96.0
A	MRC	M-50	52100	Turbo 15 (7808)	4.5 gm/hr	3.43	24.6
B	MRC	M-50	52100	Turbo 15 (7808)	8.0 gm/hr	1.90	11.5
C	MRC	M-50	52100	Turbo 15 (7808)	4.5 gm/hr	15.0	52.0
D	MRC	M-50	52100	Mineral Oil (WS4138)	4.5 gm/hr	13.5	42.0

TABLE III

LOT DK (REFERENCE BALL)
FATIGUE LIFE - FIBER ORIENTATION
CORRELATION ON LIFE AT FAILURE POINT

Ball No.	Location of Spall	Life - End Grain	Life - Side Grain
12	Invalid		
30	End Grain	3.3	
2	Side Grain		4.5
15	Invalid		
35	Side Grain		8.7
9	Side Grain		13.8
29	End Grain	15.0	
20	Suspended		
16	Invalid		
14	End Grain	17.2	
4	End Grain	21.1	
21	Side Grain		25.5
1	Invalid		
3	End Grain	28.5	
17	End Grain	29.8	
8	Invalid		
32	End Grain	31.1	
18	Side Grain		39.5
26	Invalid		
23	Side Grain		55.7
31	End Grain	57.5	
13	Side Grain		83.4
38	Invalid		
7	Invalid		
25	End Grain	129.5	
36	Suspended		
24	End Grain	138.1	
37	Side Grain		143.1
28	Suspended		
	Total Hours	471.1	309.8
Balance Suspended			
	Mean Life	47.1	51.6
	Median Life	29.1	32.5

TABLE IV

LOT DN (DOFT REFERENCE BALLS Rc 58)
FATIGUE LIFE - FIBER ORIENTATION
CORRELATION ON LIFE AT FAILURE POINT

Ball No.	Location of Spall	Life - End Grain	Life Side Grain
8	End Grain	1.9	
14	Side Grain		2.5
13	End Grain	2.9	
6	End Grain	2.9	
4	End Grain	3.0	
15	End Grain	3.0	
40	Side Grain		3.8
23	Side Grain		4.1
7	Side Grain		4.6
26	Side Grain		6.8
28	End Grain	8.8	
16	Side Grain		22.5
25	End Grain	31.4	
20	Side Grain		42.0
3	Side Grain		43.5
32	End Grain	52.6	
1	End Grain	55.4	
39	Side Grain		65.0
33	End Grain	103.2	
9	End Grain	126.3	
36	Side Grain		146.5
27	End Grain	148.5	
	Total Hours	539.9	342.2
	Mean Life	45.0	34.2
	Median Life	20.1	14.6

TABLE V

LOT DM (PINCH-OFF)
FATIGUE LIFE - FIBER ORIENTATION
CORRELATION ON LIFE AT FAILURE POINT

Ball No.	Location of Spall	Life - End Grain	Life - Side Grain
1	Side Grain		0.7
3	End Grain	0.7	
5	End Grain	1.3	
17	Invalid		
8	End Grain	1.8	
37	Side Grain		2.0
2	Side Grain		2.0
12	Side Grain		2.7
10	Side Grain		2.9
39	End Grain	3.2	
36	Side Grain		3.9
7	End Grain	5.3	
34	End Grain	6.0	
38	End Grain	8.5	
23	Side Grain		9.1
24	End Grain	9.2	
13	Invalid		
21	End Grain	10.5	
9	Side Grain		11.3
6	Side Grain		11.6
27	Side Grain		11.6
40	Side Grain		12.1
32	Side Grain		12.3
28	Invalid		
31	Side Grain		13.0
33	End Grain	13.4	
19	Side Grain		13.6
35	Side Grain		14.0
11	Side Grain		14.2
29	Side Grain		15.2
26	End Grain	16.3	
22	End Grain	19.8	
15	End Grain	20.2	
30	End Grain	22.3	
4	End Grain	22.8	
25	End Grain	27.9	
14	Side Grain		33.3
18	Side Grain		39.9
20	Side Grain		41.0
16	Side Grain		119.8
	Total Hours	189.2	386.8
	Mean Life	11.8	18.4
	Median Life	9.8	12.1

TABLE VI

LOT EB (PEENED AT 1200°F)
FATIGUE LIFE - FIBER ORIENTATION
CORRELATION ON LIFE AT FAILURE POINT

Ball No.	Location of Spall	Life - End Grain	Life - Side Grain
43	End Grain	0.2	
14	End Grain	1.7	
15	Side Grain		6.5
32	End Grain	9.1	
24	End Grain	9.7	
33	End Grain	10.8	
6	End Grain	12.3	
10	Side Grain		18.4
27	Invalid		
13	Side Grain		27.3
35	Invalid		
18	End Grain	47.0	
20	Side Grain		49.8
16	End Grain	60.8	
37	End Grain	73.5	
30	End Grain	87.8	
34	End Grain	96.7	
42	Side Grain		126.7
25	Side Grain		153.7
26	Invalid		
21	Invalid		
1	End Grain	206.3	
4	End Grain	206.4	
	Total Hours	822.3	382.4
	Mean Life	63.3	63.7
	Median Life	47.0	38.5

TABLE VII

LOT #8 (REFERENCE)
FATIGUE LIFE - FIBER ORIENTATION
CORRELATION ON LIFE AT FAILURE POINT

Ball No.	Location of Spall	Life - End Grain	Life - Side Grain
12	Side Grain		2.7
11	Side Grain		3.3
13	Invalid		
20	End Grain	8.8	
1	End Grain	13.1	
7	End Grain	14.3	
4	End Grain	19.3	
18	Side Grain		19.8
31	End Grain	23.7	
2	End Grain	31.1	
15	End Grain	31.3	
21	Side Grain		37.5
6	End Grain	42.1	
19	Side Grain		42.2
28	Suspended		
14	End Grain	50.8	
9	Suspended		
27	Side Grain		60.5
22	Side Grain		62.8
30	End Grain	71.0	
17	End Grain	71.3	
29	End Grain	75.3	
25	End Grain	89.0	
8	Side Grain		93.3
16	Side Grain		168.0
26	Suspended		
5	Suspended		
33	Suspended		
32	Suspended		
10	End Grain	189.7	
3	Suspended		
	Total Hours	730.8	490.1
	Mean Life	52.2	54.5
	Median Life	36.7	42.2

TABLE VIII

LOT #5 (EXPLOSIVE HARDENED Rc 60)
FATIGUE LIFE - FIBER ORIENTATION
CORRELATION ON LIFE AT FAILURE POINT

Ball No.	Location of Spall	Life - End Grain	Life - Side Grain
34	Invalid		
31	End Grain	0.9	
35	End Grain	1.6	
29	End Grain	1.9	
7	Side Grain		3.7
3	End Grain	3.9	
25	Invalid		
32	Side Grain		6.6
6	End Grain	11.1	
28	Side Grain		14.9
2	End Grain	17.8	
19	Side Grain		19.3
4	Side Grain		19.4
26	Side Grain		19.8
21	Side Grain		20.0
18	End Grain	21.8	
30	Invalid		
27	End Grain	24.8	
14	End Grain	28.7	
17	Invalid		
13	End Grain	44.6	
33	Invalid		
10	End Grain	54.0	
12	End Grain	70.6	
11	End Grain	72.3	
15	Invalid		
20	End Grain	79.8	
23	Suspended		
8	End Grain	80.8	
	Total Hours	514.6	103.7
	Mean Life	34.3	14.8
	Median Life	24.8	19.3

TABLE IX

LOT #7 (EXPLOSIVE HARDENED Rc 15)
FATIGUE LIFE - FIBER ORIENTATION
CORRELATION ON LIFE AT FAILURE POINT

Ball No.	Location of Spall	Life - End Grain	Life - Side Grain
28	End Grain	2.0	
36	Side Grain		2.0
11	End Grain	2.2	
34	Side Grain		2.9
22	Side Grain		3.4
17	Side Grain		4.3
26	End Grain	4.6	
32	Side Grain		6.0
14	Side Grain		7.4
6	End Grain	7.7	
39	Side Grain		8.3
19	End Grain	8.7	
29	End Grain	11.2	
31	Side Grain		12.2
21	End Grain	12.7	
3	End Grain	12.9	
10	End Grain	16.0	
18	Side Grain		16.0
30	Side Grain		16.8
5	Side Grain		20.0
12	Suspended		
2	Side Grain		23.0
27	End Grain	23.0	
20	End Grain	26.0	
24	Side Grain		26.2
4	Side Grain		26.3
1	End Grain	28.6	
8	Side Grain		28.8
16	Side Grain		31.5
25	Side Grain		35.6
33	Suspended		
15	Side Grain		68.3
	Total Hours	155.6	339.2
	Mean Life	12.9	18.8
	Median Life	11.9	16.4

TABLE X

LOT 22A
FATIGUE LIFE - FIBER ORIENTATION
CORRELATION ON LIFE AT FAILURE POINT

Ball No.	Location of Spall	Life - End Grain	Life - Side Grain
22	Side Grain		5.0
27	End Grain	5.6	
18	Side Grain		6.2
28	Side Grain		8.4
9	End Grain	9.6	
11	Side Grain		9.8
21	End Grain	10.0	
12	End Grain	11.4	
32	End Grain	14.4	
31	Side Grain		17.5
4	Side Grain		18.0
15	Side Grain		21.1
1	Side Grain		26.8
5	Invalid		
10	End Grain	31.0	
3	Side Grain		35.5
20	Side Grain		36.0
24	End Grain	37.4	
17	Side Grain		45.2
8	Side Grain		46.6
26	Side Grain		48.1
30	Side Grain		48.8
7	Side Grain		50.7
6	End Grain	51.3	
2	Side Grain		52.7
29	Suspended		
16	Side Grain		63.8
13	End Grain	87.8	
25	Side Grain		98.9
19	End Grain	91.4	
	Total Hours	349.9	642.7
	Mean Life	35.0	35.7
	Median Life	22.7	36.0

TABLE XI

LOT #10 (ROOM TEMPERATURE PEENED)
FATIGUE LIFE - FIBER ORIENTATION
CORRELATION ON LIFE AT FAILURE POINT

Ball No.	Location of Spall	Life - End Grain	Life - Side Grain
12	Side Grain		8.4
27	Side Grain		13.2
7	End Grain	23.6	
20	Side Grain		28.1
23	End Grain	28.2	
10	Invalid		
24	Invalid		
11	Invalid		
18	Side Grain		36.0
17	Side Grain		39.3
21	Side Grain		43.0
8	End Grain	45.1	
1	End Grain	50.2	
5	Side Grain		52.1
30	Side Grain		55.9
13	Side Grain		64.1
9	Side Grain		65.1
6	End Grain	69.1	
15	Side Grain		75.7
26	Side Grain		86.0
	Total Hours	216.2	566.9
	Mean Life	43.2	47.2
	Median Life	45.1	47.5

TABLE XII

LOT #11 (PEENED AT 900°F)
FATIGUE LIFE FIBER ORIENTATION
CORRELATION ON LIFE AT FAILURE POINT

Ball No.	Location of Spall	Life - End Grain	Life - Side Grain
27	Invalid		
5	End Grain	7.6	
23	End Grain	9.9	
25	Invalid		
3	End Grain	14.7	
4	End Grain	16.2	
26	End Grain	17.3	
7	Side Grain		19.5
9	End Grain	19.7	
20	Invalid		
17	End Grain	25.0	
24	Side Grain		27.5
10	Invalid		
28	Side Grain		30.0
14	Side Grain		33.4
31	Side Grain		33.5
30	End Grain	37.8	
1	Side Grain		38.6
15	Side Grain		38.6
6	Side Grain		39.2
13	End Grain	58.2	
21	Side Grain		64.[illegible]
19	Invalid		
16	Side Grain		73.9
12	Invalid		
8	Invalid		
11	Side Grain		208.0
	Total Hours	206.4	607.1
	Mean Life	22.9	55.2
	Median Life	17.3	38.6

TABLE XIII

PROBABILITY STUDY

Lot Number	No. of End Fiber Failures	No. of Side Fiber Failures	Total No. of Failures	Actual Probability of End Fiber Failure	Actual Probability of Side Fiber Failures	Theoretical Probability of End Fiber Failures	Theoretical Probability of Side Fiber Failures
(Reference)							
DK	10	8	18	0.55	0.44	0.375	0.625
DN	12	10	22	0.54	0.45	0.375	0.625
6	14	9	23	0.61	0.39	0.318	0.682
(Peened)							
10	5	12	17	0.29	0.71	0.318	0.682
11	9	11	20	0.45	0.55	0.318	0.682
EB	13	6	19	0.68	0.31	0.375	0.625
xplosive Hardened)							
5	15	7	22	0.68	0.32	0.318	0.682
7	12	18	30	0.40	0.60	0.318	0.682
(Non-Metallic)							
24	7	12	19	0.37	0.63	0.318	0.682
25	5	21	26	0.19	0.81	0.318	0.682
26	9	16	25	0.36	0.64	0.318	0.682
(90% Reduction)							
22A	10	18	28	0.37	0.64	0.318	0.682
(Pinch-Off)							
DM	16	21	37	0.43	0.57	0.375	0.625

TABLE XIV

LOT #24 (SULFIDES)
FATIGUE LIFE - FIBER ORIENTATION
CORRELATION ON LIFE AT FAILURE POINT

Ball No.	Location of Spall	Life - End Grain	Life - Side Grain
36	End Grain	8.2	
39	Invalid		
43	Side Grain		12.9
16	Side Grain		17.5
47	Side Grain		17.9
37	Side Grain		23.0
22	End Grain	26.2	
1	Side Grain		27.1
45	Invalid		
38	Invalid		
26	End Grain	32.8	
17	Invalid		
42	Side Grain		37.5
34	End Grain	38.9	
32	Side Grain		40.7
18	Side Grain		44.5
28	Invalid		
15	Side Grain		60.7
8	End Grain	72.6	
29	End Grain	77.5	
33	Side Grain		81.6
19	Invalid		
21	Side Grain		93.5
11	End Grain	105.0	
48	Side Grain		114.7
9	Side Grain		140.3
30	Suspended		
	Total Hours	361.2	711.9
	Mean Life	51.6	54.8
	Median Life	38.9	40.7

TABLE XV

LOT #25 (HIGH SILICATES)
FATIGUE LIFE - FIBER ORIENTATION
CORRELATION ON LIFE AT FAILURE POINT

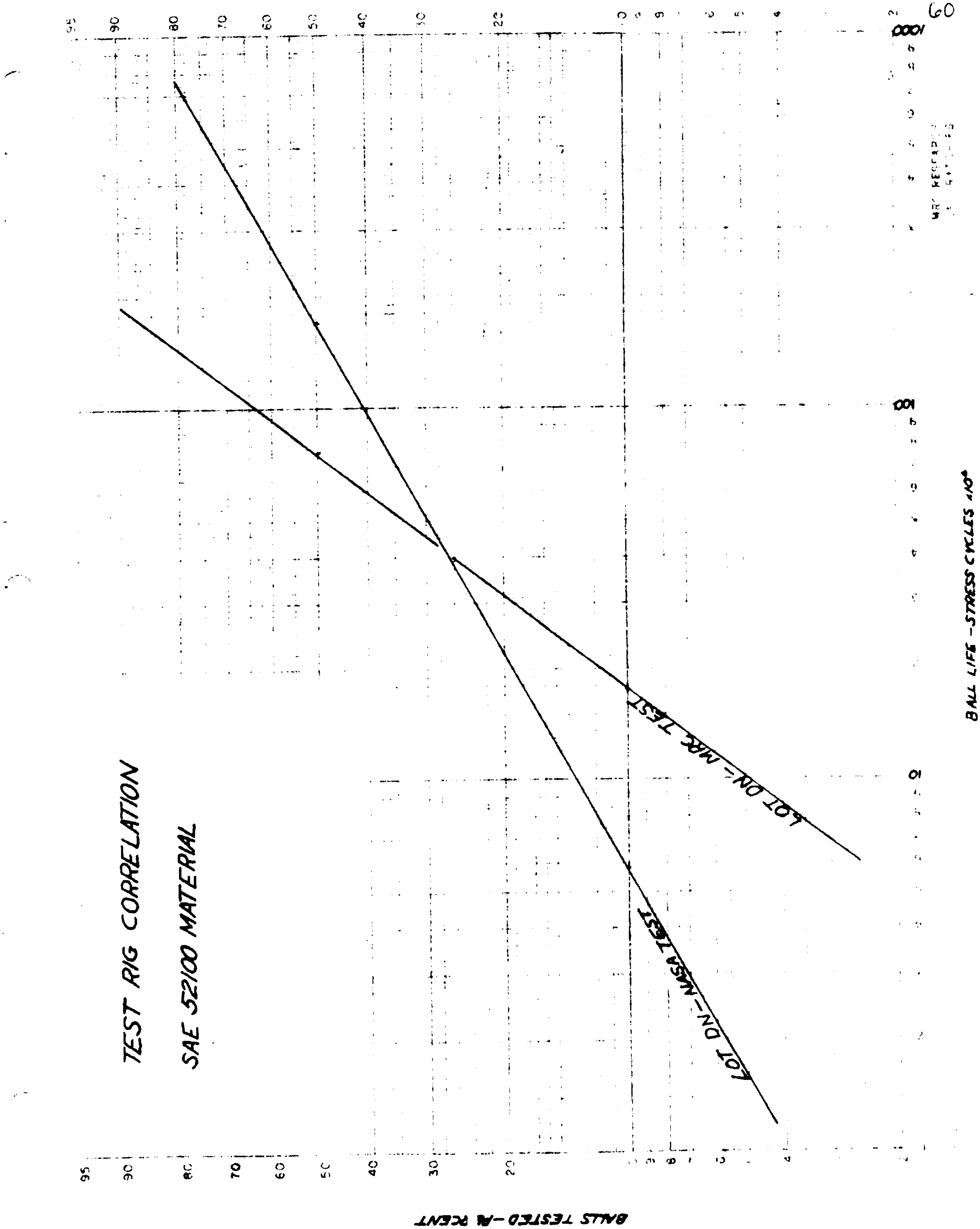
Ball No.	Location of Spall	Life - End Grain	Life - Side Grain
19	Side Grain		13.7
36	Side Grain		15.7
34	Side Grain		19.0
20	Side Grain		23.7
38	Side Grain		28.5
4	End Grain	30.0	
11	End Grain	30.7	
3	Side Grain		38.8
41	Side Grain		39.2
1	Side Grain		39.7
39	Side Grain		47.4
13	Side Grain		55.0
37	Side Grain		57.5
28	Invalid		
22	Side Grain		59.9
24	Side Grain		61.8
31	Invalid		
40	Side Grain		67.3
14	End Grain	108.8	
29	Side Grain		113.7
23	Side Grain		128.1
27	Side Grain		169.5
30	End Grain	171.7	
5	Side Grain		183.5
15	End Grain	189.8	
32	Suspended		
6	Side Grain		254.6
9	Side Grain		280.1
10	Side Grain		282.0
18	Suspended		
25	Suspended		
	Total Hours	531.0	1978.7
	Mean Life	106.2	94.2
	Median Life	108.8	57.5

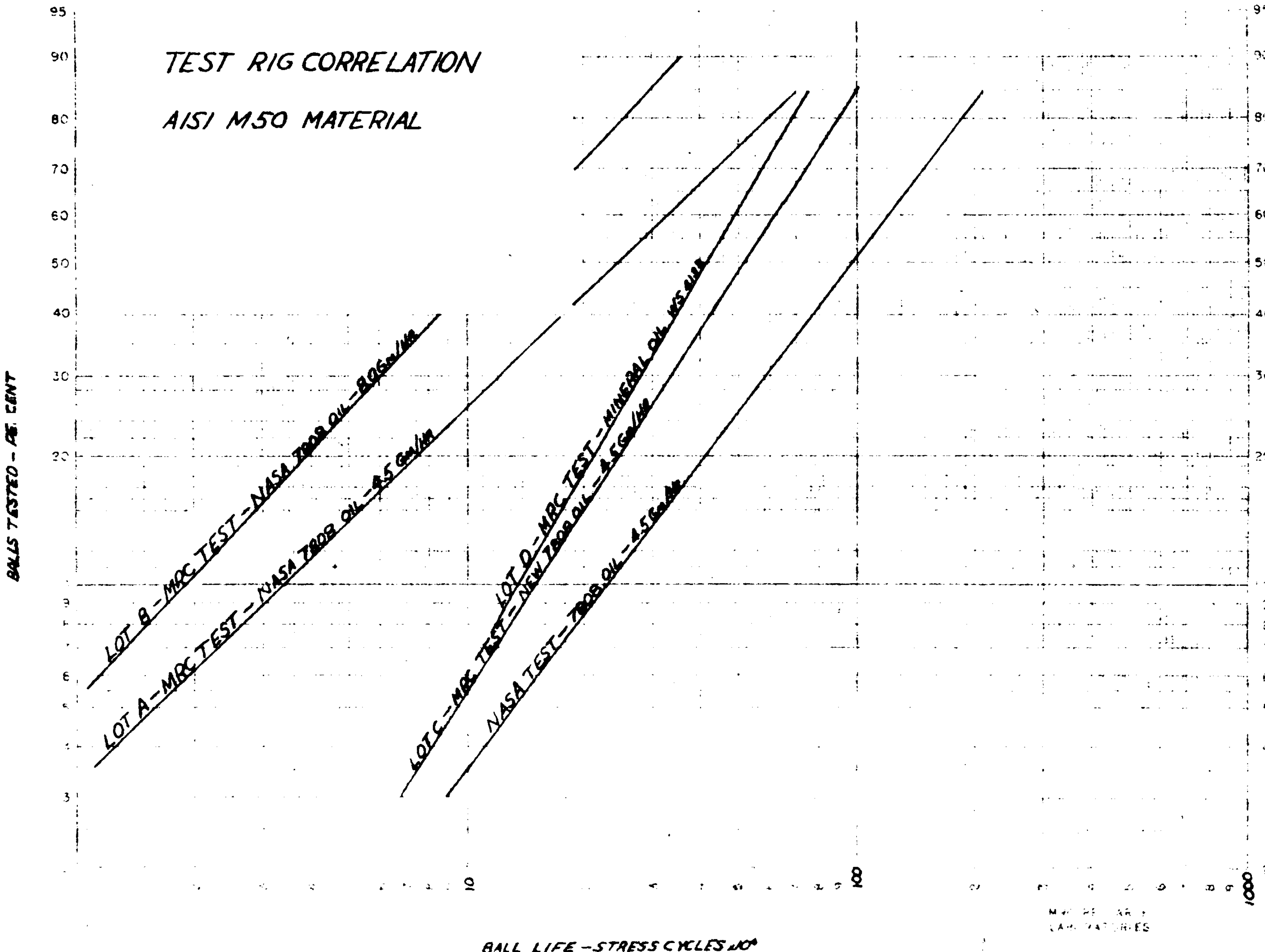
TABLE XVI

LOT #26 (HIGH ALUMINATES)
FATIGUE LIFE - FIBER ORIENTATION
CORRELATION ON LIFE AT FAILURE POINT

Ball No.	Location of Spall	Life - End Grain	Life - Side Grain
1	Side Grain		1.3
14	Side Grain		2.8
37	Invalid		
10	Side Grain		3.7
29	Side Grain		3.7
11	Side Grain		5.6
20	Invalid		
34	Side Grain		11.9
31	End Grain	12.3	
9	Side Grain		15.4
23	Invalid		
38	Side Grain		19.4
26	End Grain	24.0	
17	End Grain	26.3	
3	Side Grain		28.0
6	End Grain	38.1	
22	Side Grain		38.1
8	Side Grain		38.2
12	Side Grain		38.5
35	Side Grain		39.7
16	End Grain	46.6	
19	Side Grain		49.0
4	Side Grain		49.1
5	Suspended		
36	Suspended		
21	End Grain	99.7	
33	Suspended		
13	End Grain	124.8	
2	Side Grain		130.6
15	End Grain	130.9	
7	End Grain	160.5	
18	Suspended		
	Total Hours	663.2	475.0
	Mean Life	73.7	29.7
	Median Life	46.6	23.7

GRAPH 1


TEST RIG CORRELATION
SAE 52100 MATERIAL
LOT DN - MRC TEST
LOT DN - NASA TEST
BALL LIFE - STRESS CYCLES ×10⁶
BALLS TESTED - PER CENT

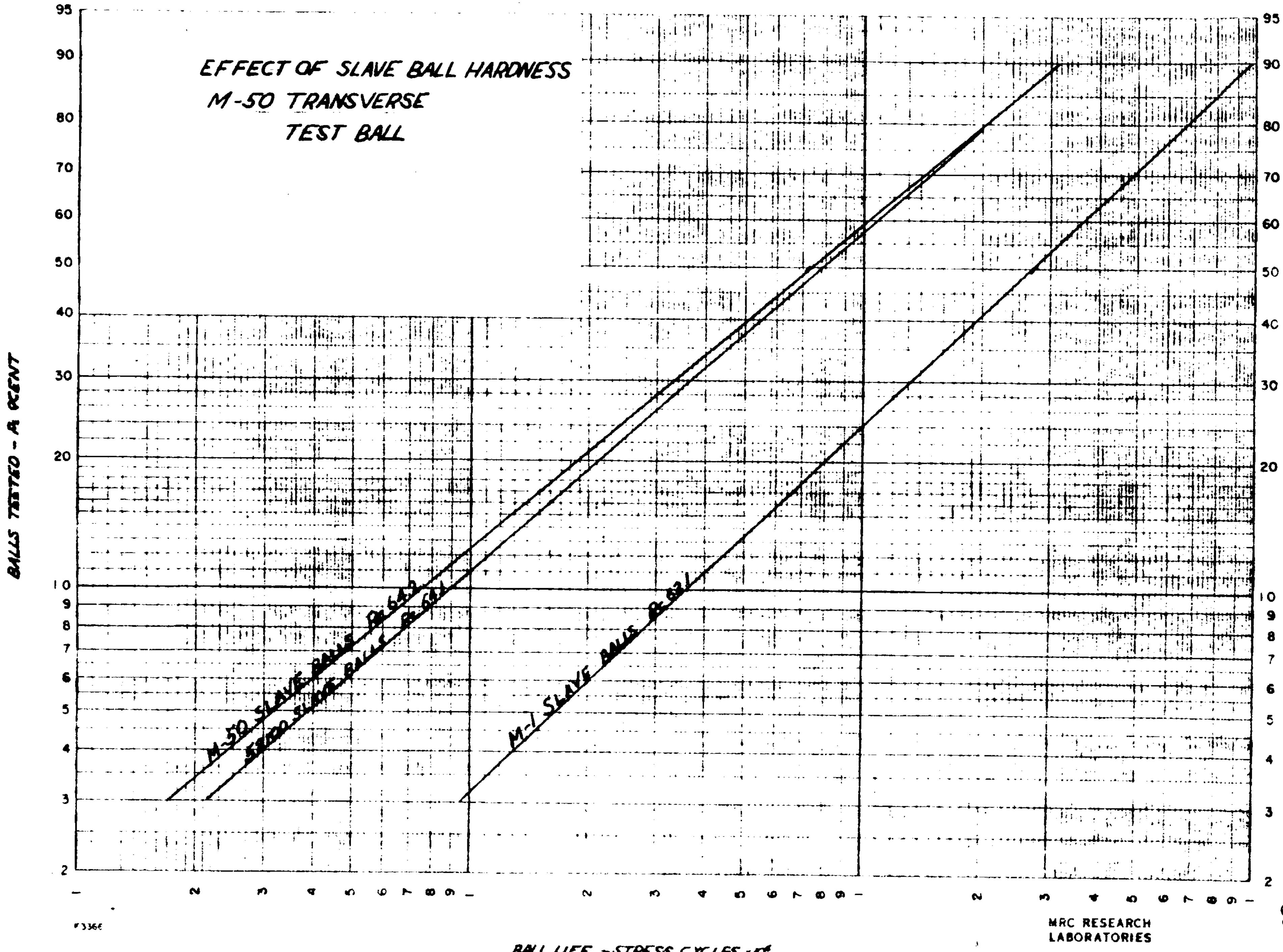


TEST RIG CORRELATION
AISI M50 MATERIAL
LOT B-MRC TEST-NASA 7808 OIL-8.0 Gm/HR
LOT A-MRC TEST-NASA 7808 OIL-4.5 Gm/HR
LOT D-MRC TEST-MINERAL OIL 1.5 GM/HR
LOT C-MRC TEST-NEW 7808 OIL-4.5 Gm/HR
NASA TEST-7808 OIL-4.5 Gm/HR
BALLS TESTED - PER CENT
BALL LIFE-STRESS CYCLES x10^6

GRAPH 2

61

GRAPH 3



EFFECT OF SLAVE BALL HARDNESS
M-50 TRANSVERSE
TEST BALL
M-50 SLAVE BALLS Rc 64.2
52100 SLAVE BALLS Rc 64.1
M-1 SLAVE BALLS Rc 62.1
BALLS TESTED - PERCENT
BALL LIFE - STRESS CYCLES
MRC RESEARCH
LABORATORIES

GRAPH 4

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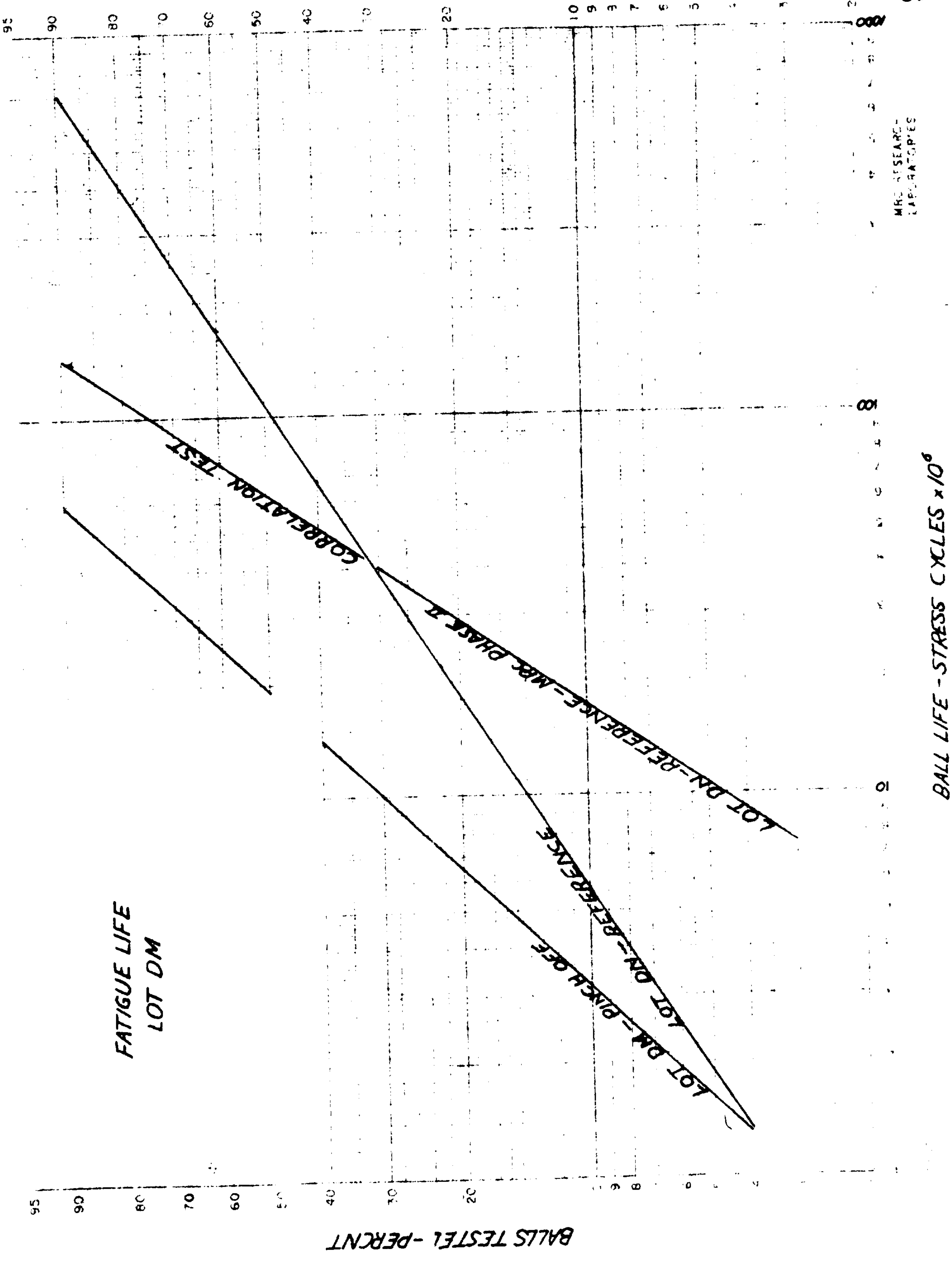
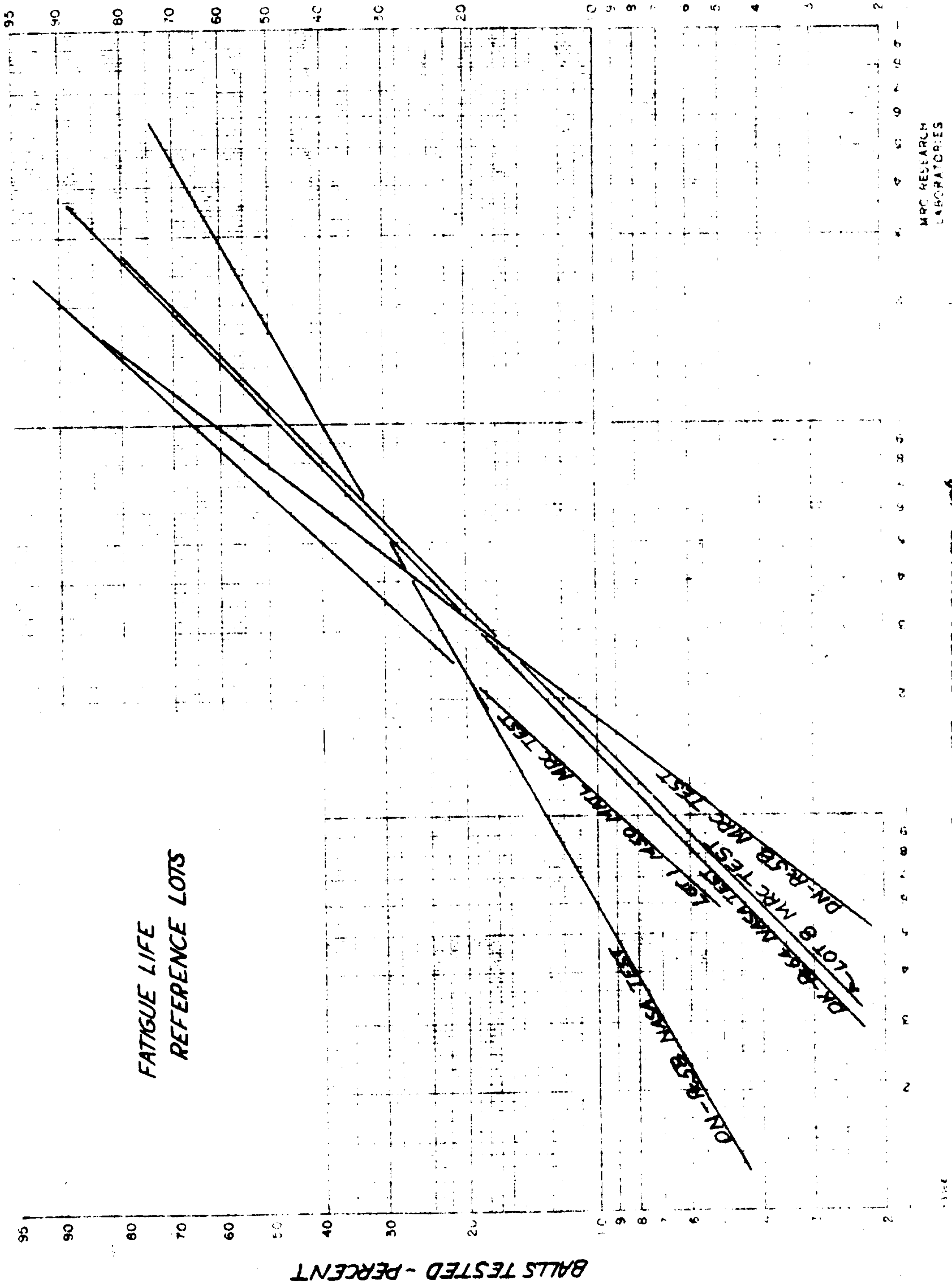
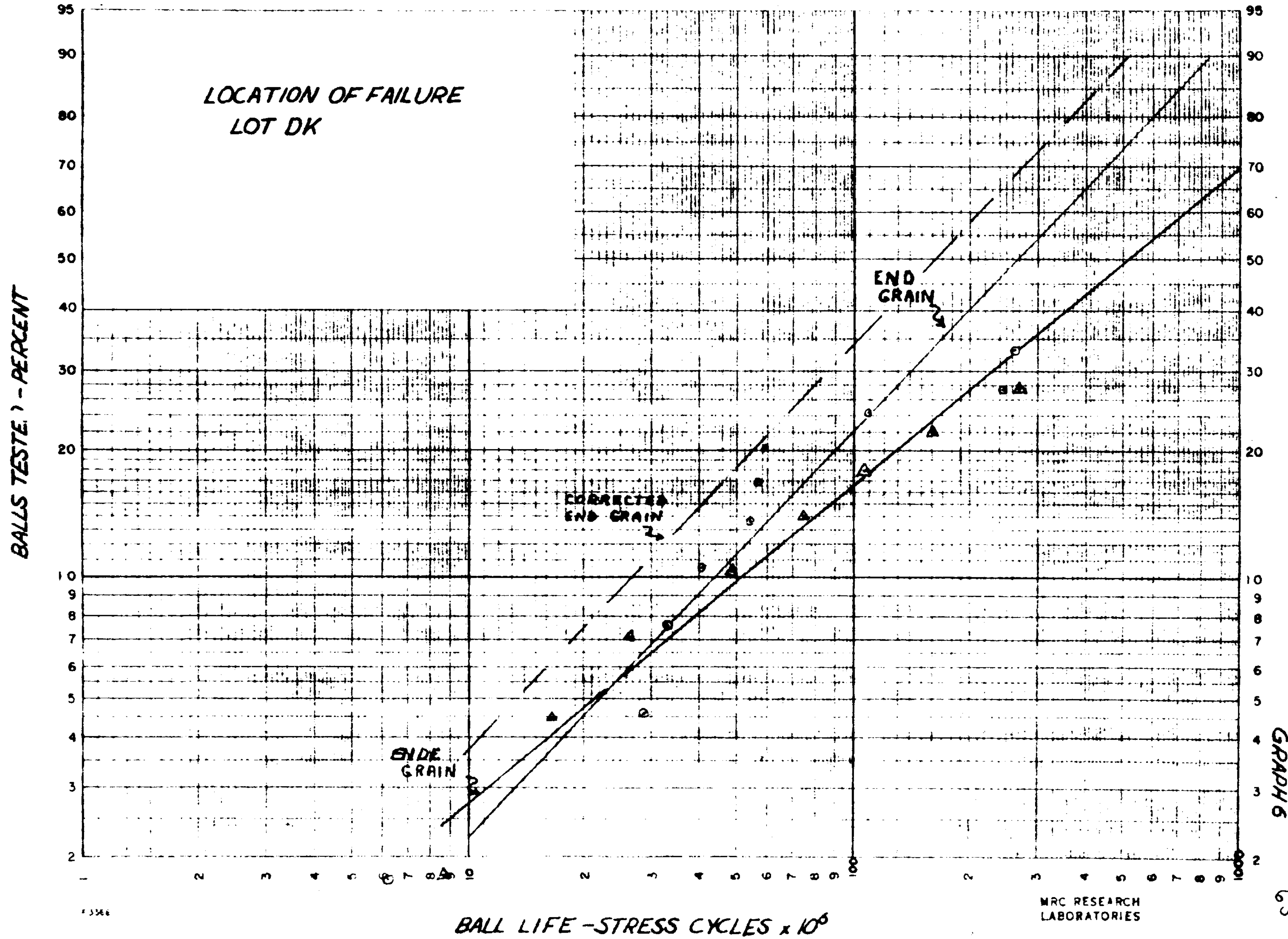
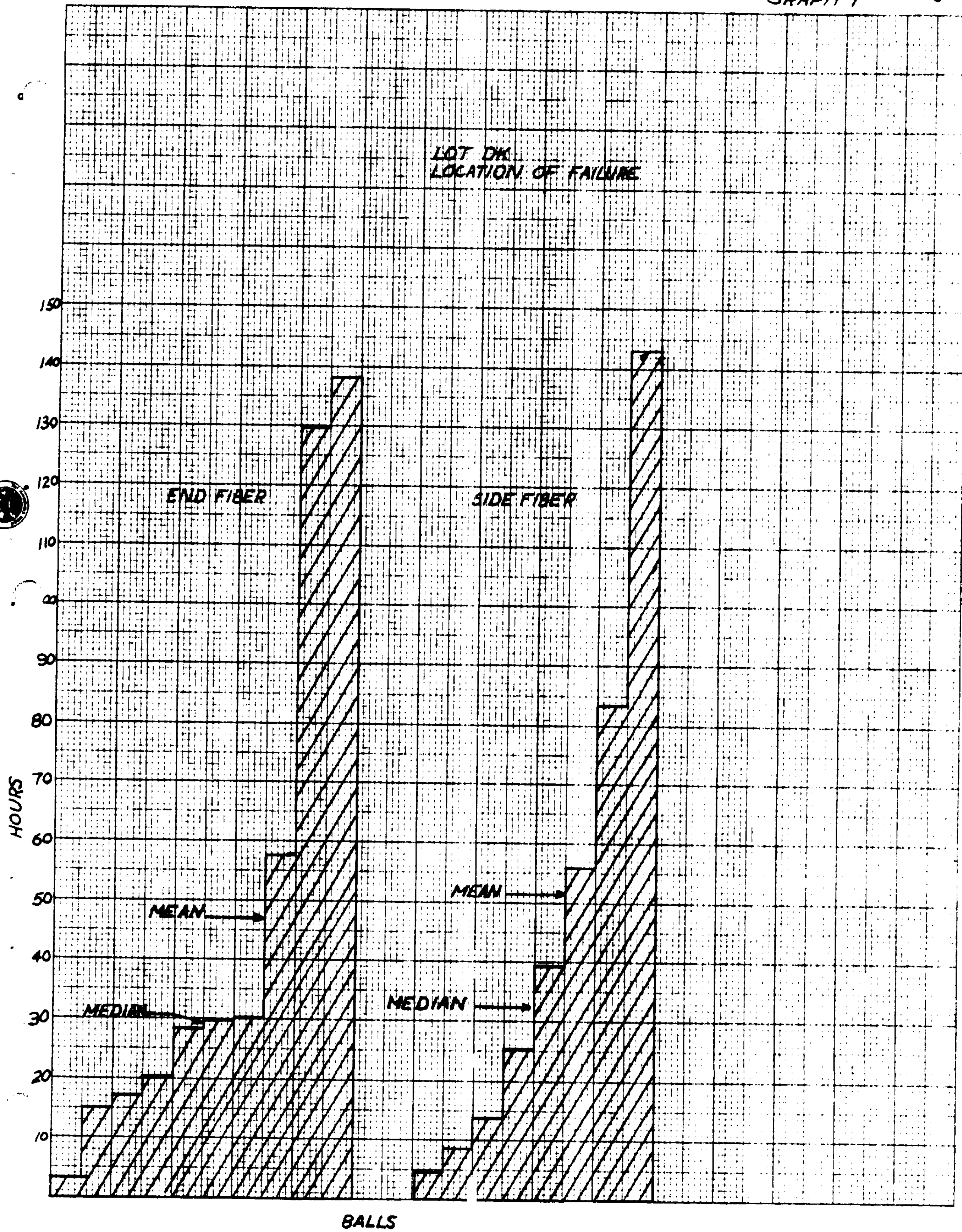

FATIGUE LIFE
LOT DM
CORRELATION TEST
LOT DN-REFERENCE-MRC PHASE II
LOT DN-REFERENCE
LOT DM-PINCH OFF
BALL LIFE - STRESS CYCLES x10^6
BALLS TESTED - PERCENT
1000
100
10

GRAPH 5

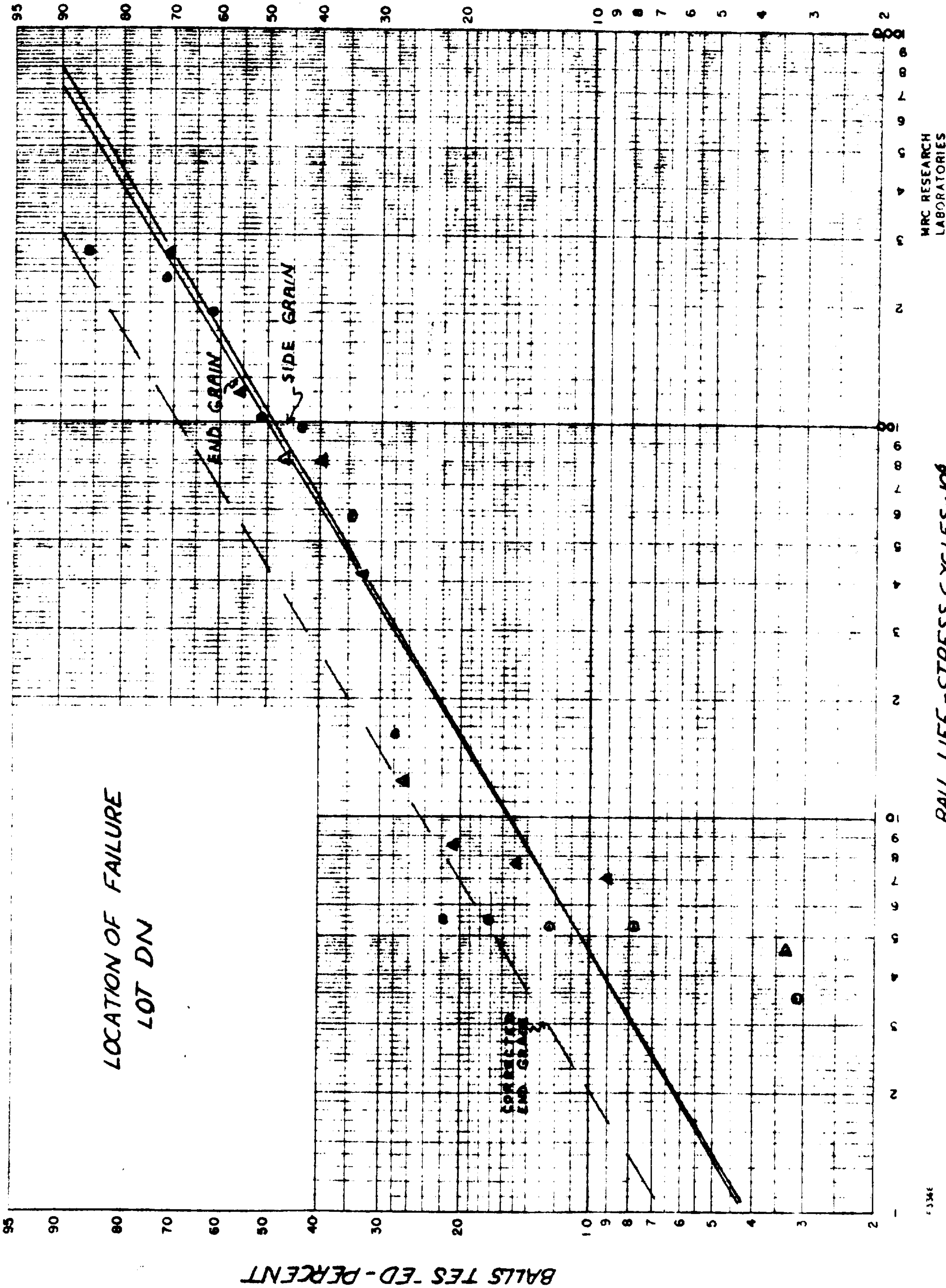


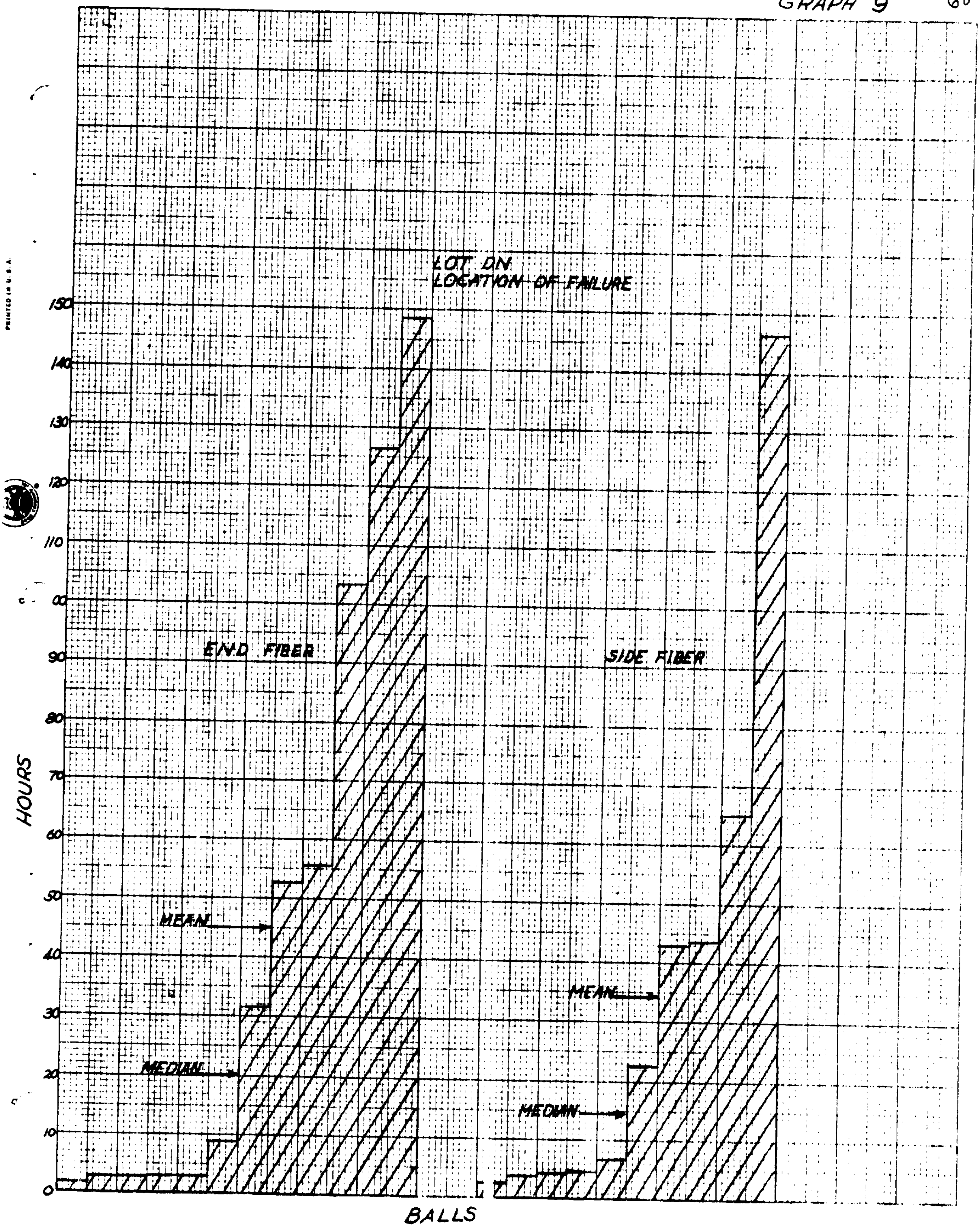
FATIGUE LIFE
REFERENCE LOTS
DN-R-5B MRC TEST
LOT B MRC TEST
DK-R-64 NASA TEST
LOT 1 4140 MATL MRC TEST
DN-R-5B NASA TEST
BALLS TESTED - PERCENT
MRC RESEARCH LABORATORIES


LOCATION OF FAILURE
LOT DK
END GRAIN
CORRECTED END GRAIN
SIDE GRAIN
BALLS TESTED - PERCENT
BALL LIFE -STRESS CYCLES x 10^6
MRC RESEARCH LABORATORIES
GRAPH 6

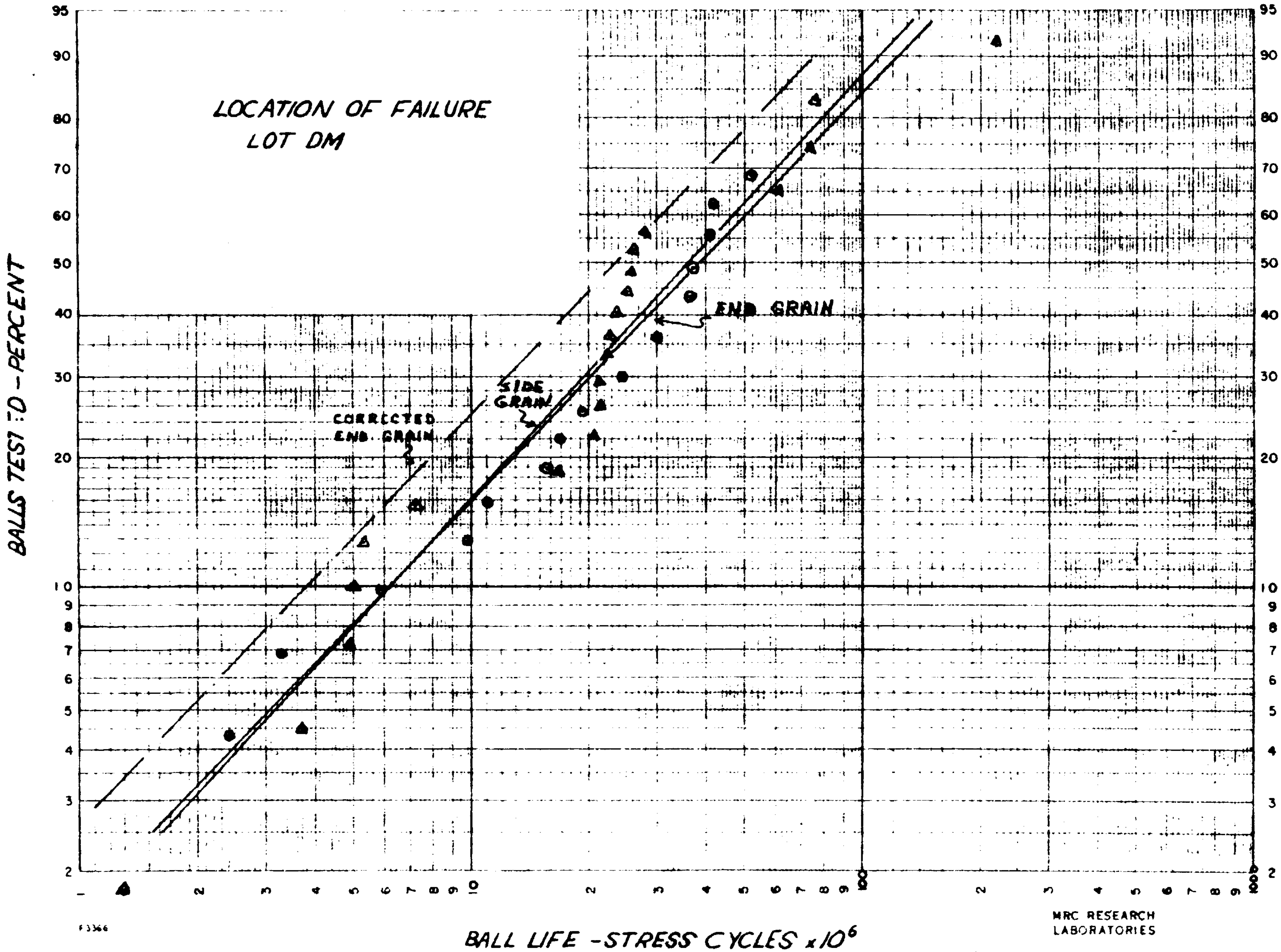

LOT DK
LOCATION OF FAILURE
END FIBER
SIDE FIBER
MEAN
MEAN
MEDIAN
MEDIAN
HOURS
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
BALLS

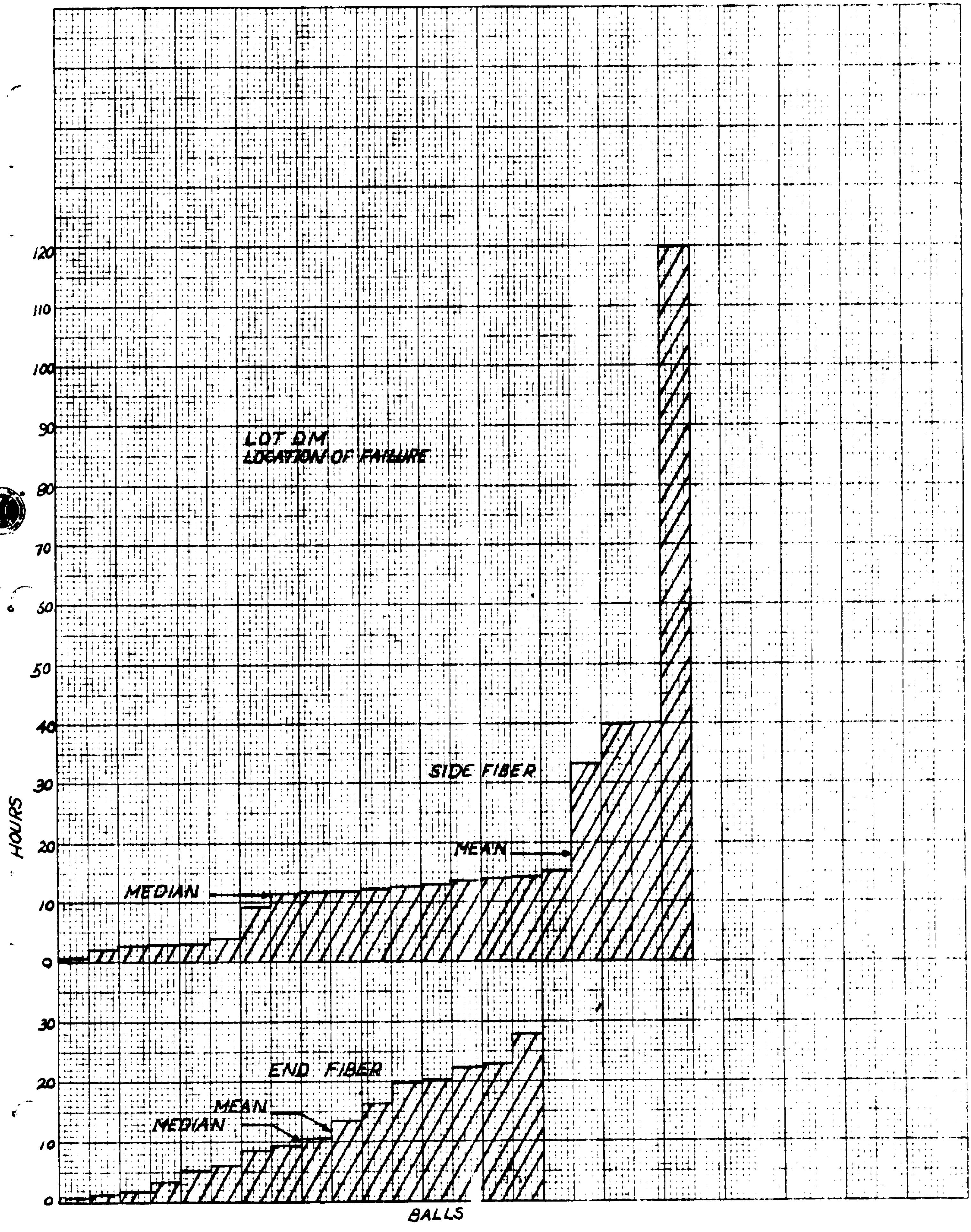
GRAPH 8


LOCATION OF FAILURE
LOT DN
END GRAIN
SIDE GRAIN
CORRECTED END GRAIN
MRC RESEARCH LABORATORIES
BALL LIFE-STRESS CYCLES x10⁶
BALLS TES -ED - PERCENT

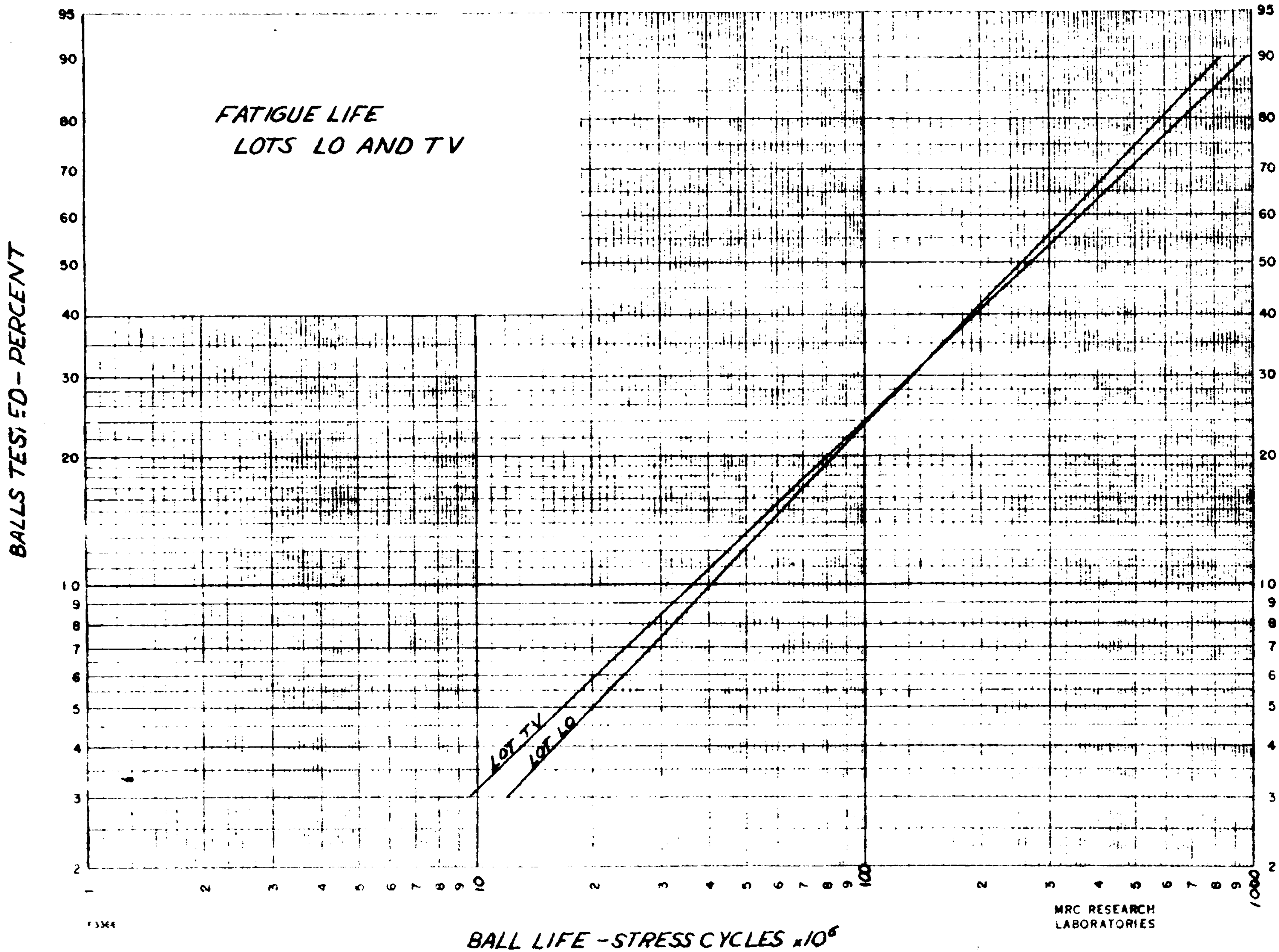

LOT DN
LOCATION OF FAILURE
HOURS
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
END FIBER
MEAN
MEDIAN
SIDE FIBER
MEAN
MEDIAN
BALLS

GRAPH 10

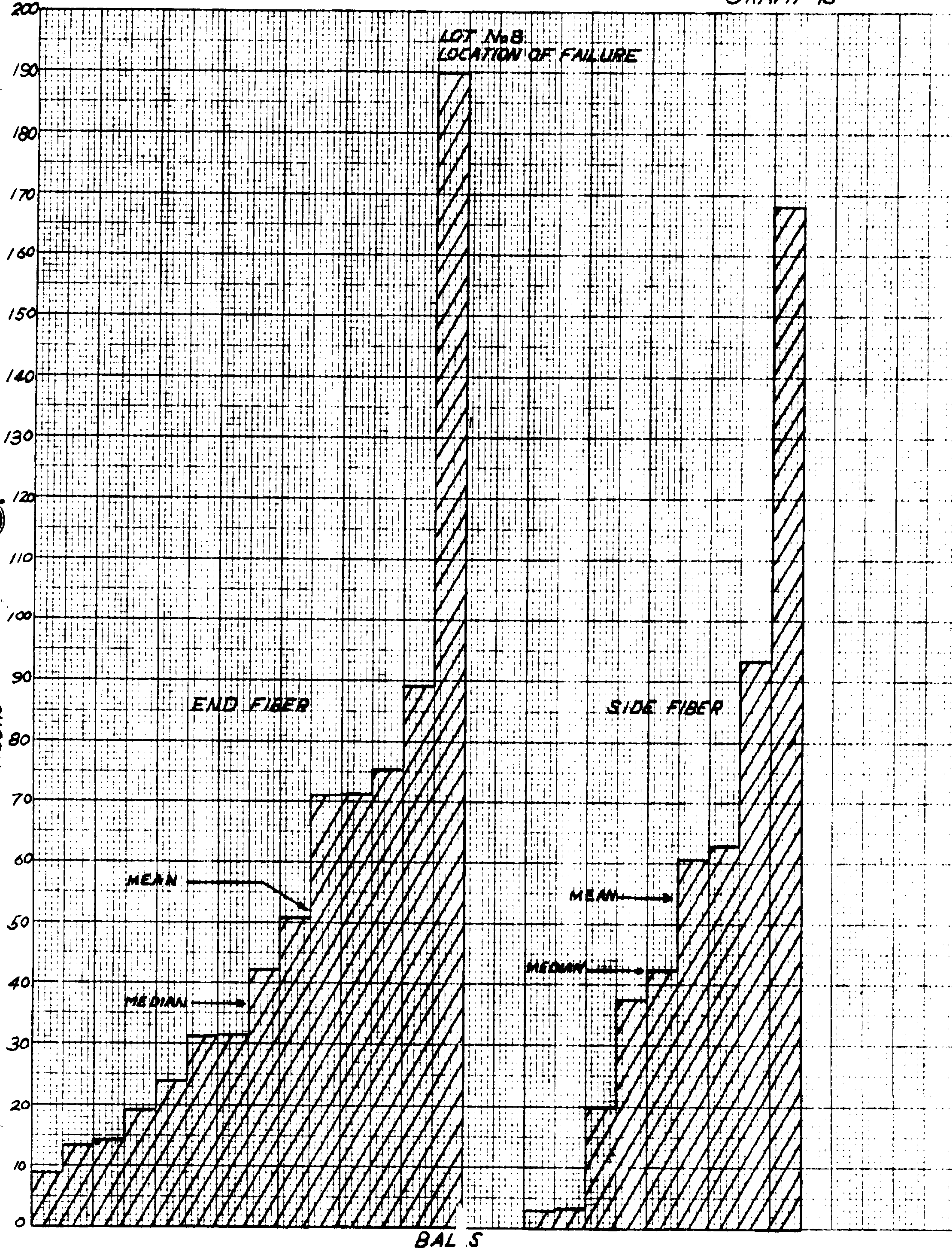

LOCATION OF FAILURE
LOT DM
END GRAIN
SIDE GRAIN
CORRECTED END GRAIN
BALLS TESTED - PERCENT
BALL LIFE - STRESS CYCLES x 10^6
MRC RESEARCH LABORATORIES
F3366

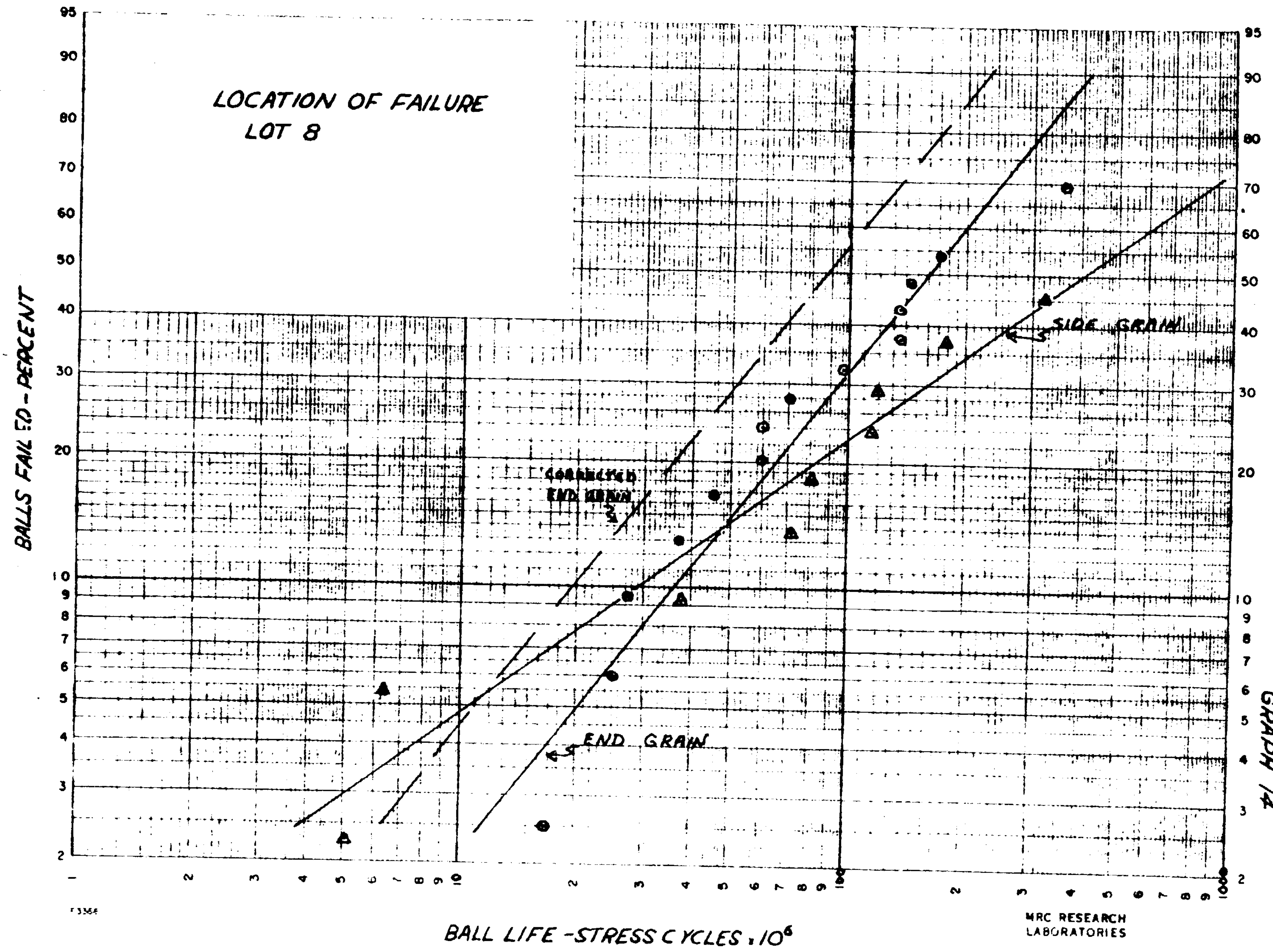

LOT DM
LOCATION OF FAILURE
HOURS
120
110
100
90
80
70
60
50
40
30
20
10
0
SIDE FIBER
MEAN
MEDIAN
30
20
10
0
END FIBER
MEAN
MEDIAN
BALLS

GRAPH 12


FATIGUE LIFE
LOTS LO AND TV
LOT TV
LOT LO
BALLS TESTED - PERCENT
BALL LIFE - STRESS CYCLES x10^6
MRC RESEARCH LABORATORIES

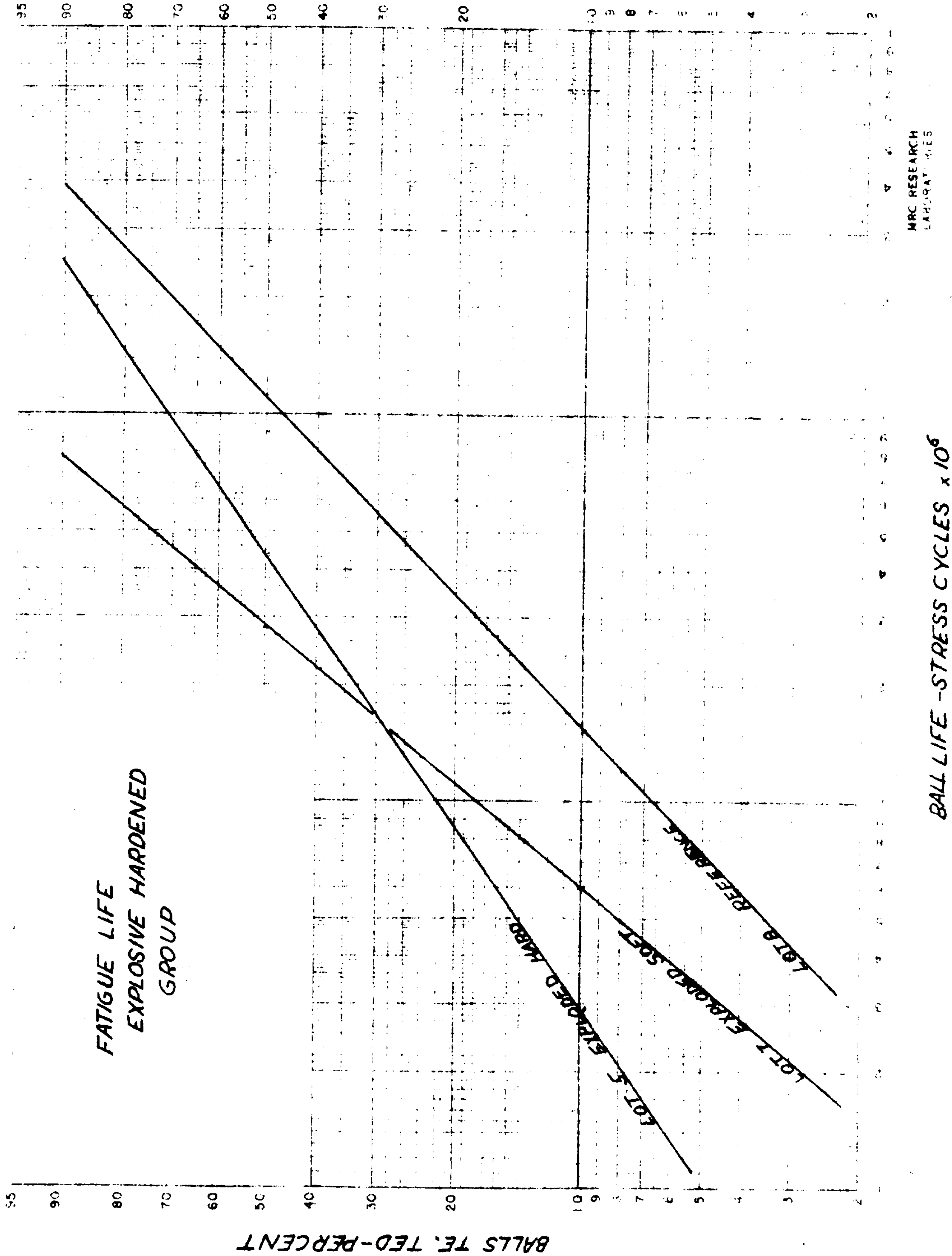
GRAPH 13


LOT No 8
LOCATION OF FAILURE
END FIBER
SIDE FIBER
MEAN
MEDIAN
MEAN
MEDIAN
HOURS
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
BALLS

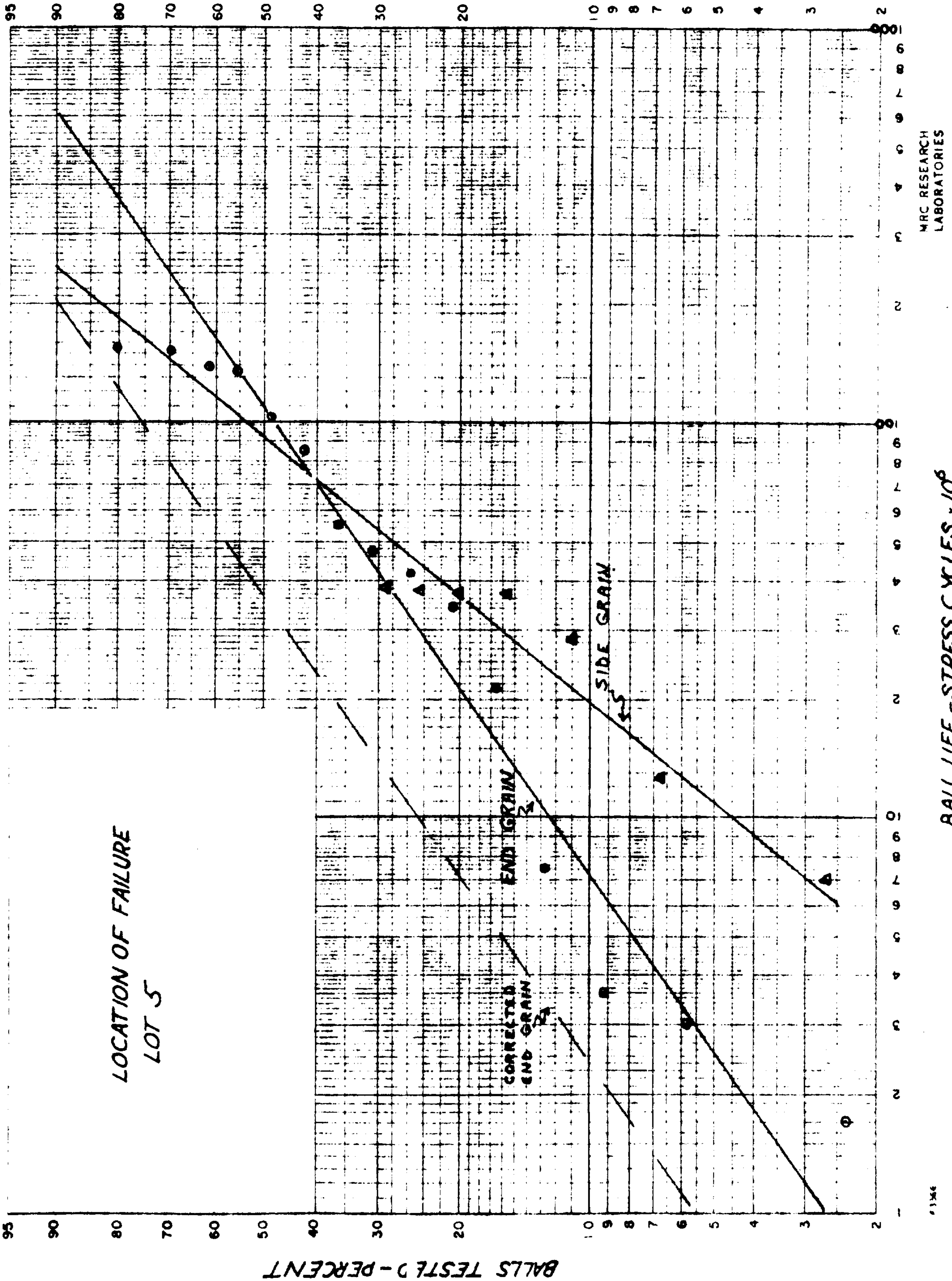


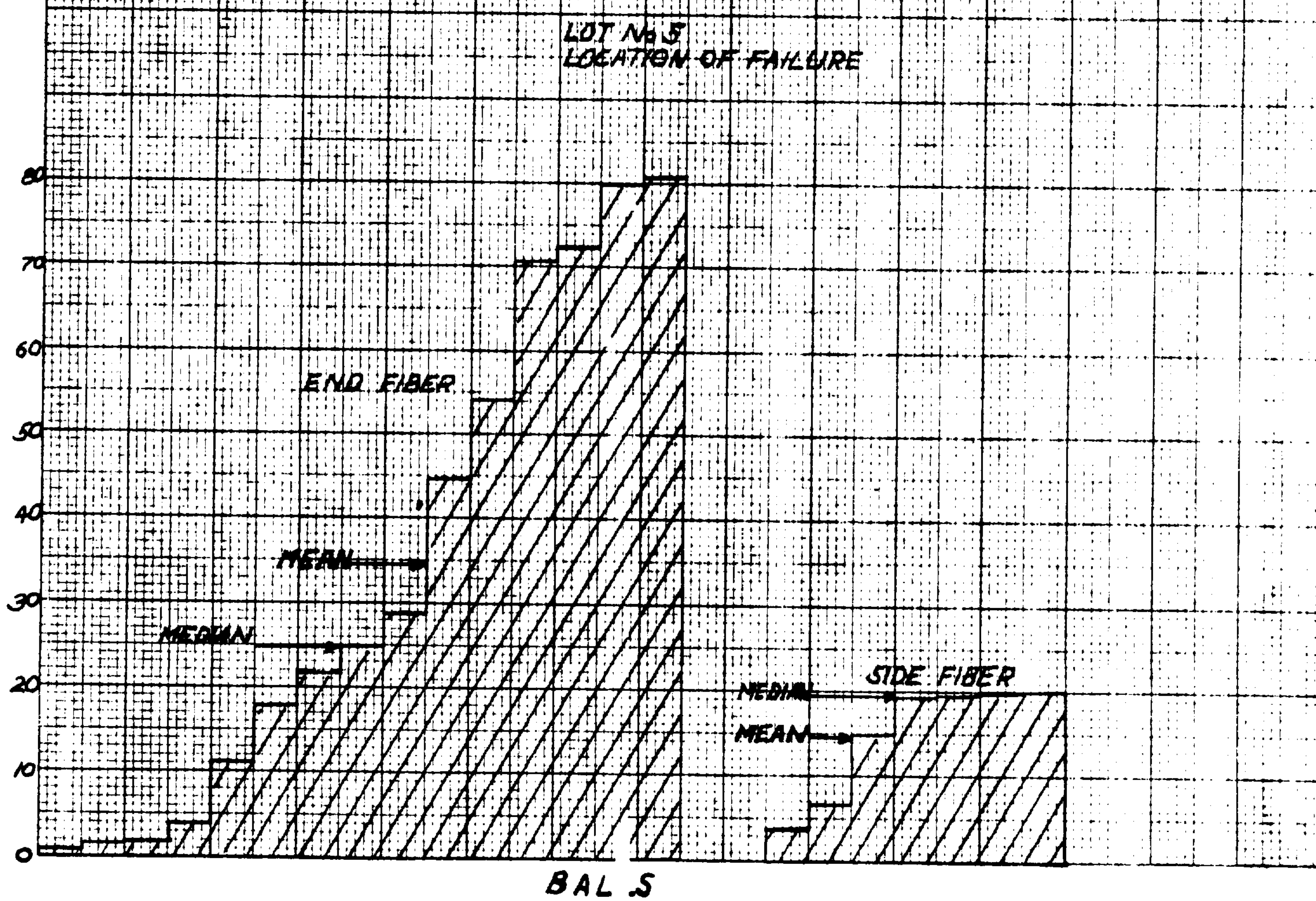
LOCATION OF FAILURE
LOT 8
CORRECTED END GRAIN
END GRAIN
SIDE GRAIN
BALLS FAILED - PERCENT
BALL LIFE - STRESS CYCLES x 10^6
GRAPH 14
MRC RESEARCH LABORATORIES

GRAPH 15

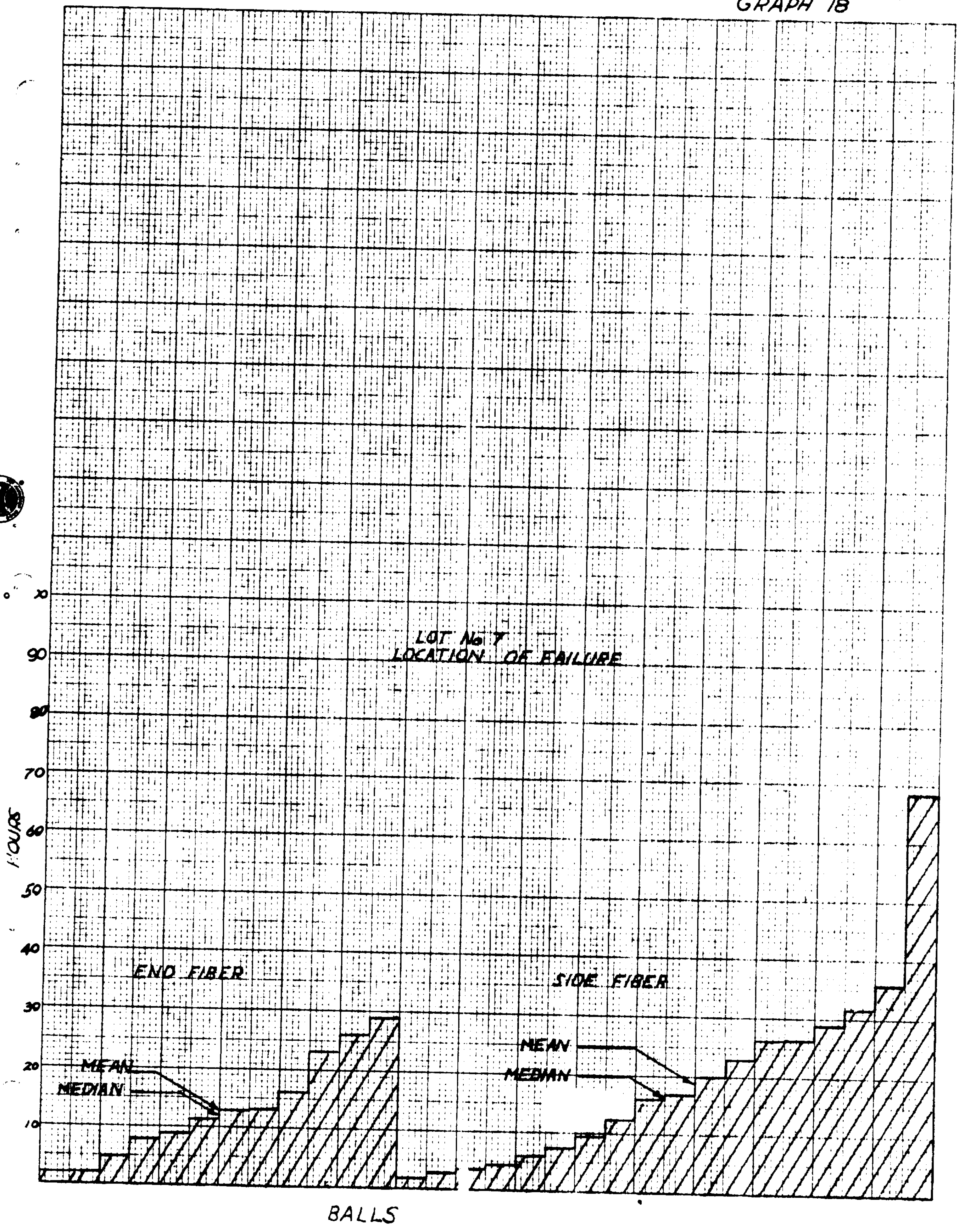

FATIGUE LIFE
EXPLOSIVE HARDENED
GROUP
BALL LIFE -STRESS CYCLES x 10^6
LOT B REFERENCE
LOT 1 EXPLODED SOFT
LOT 3 EXPLODED HARD
MRC RESEARCH

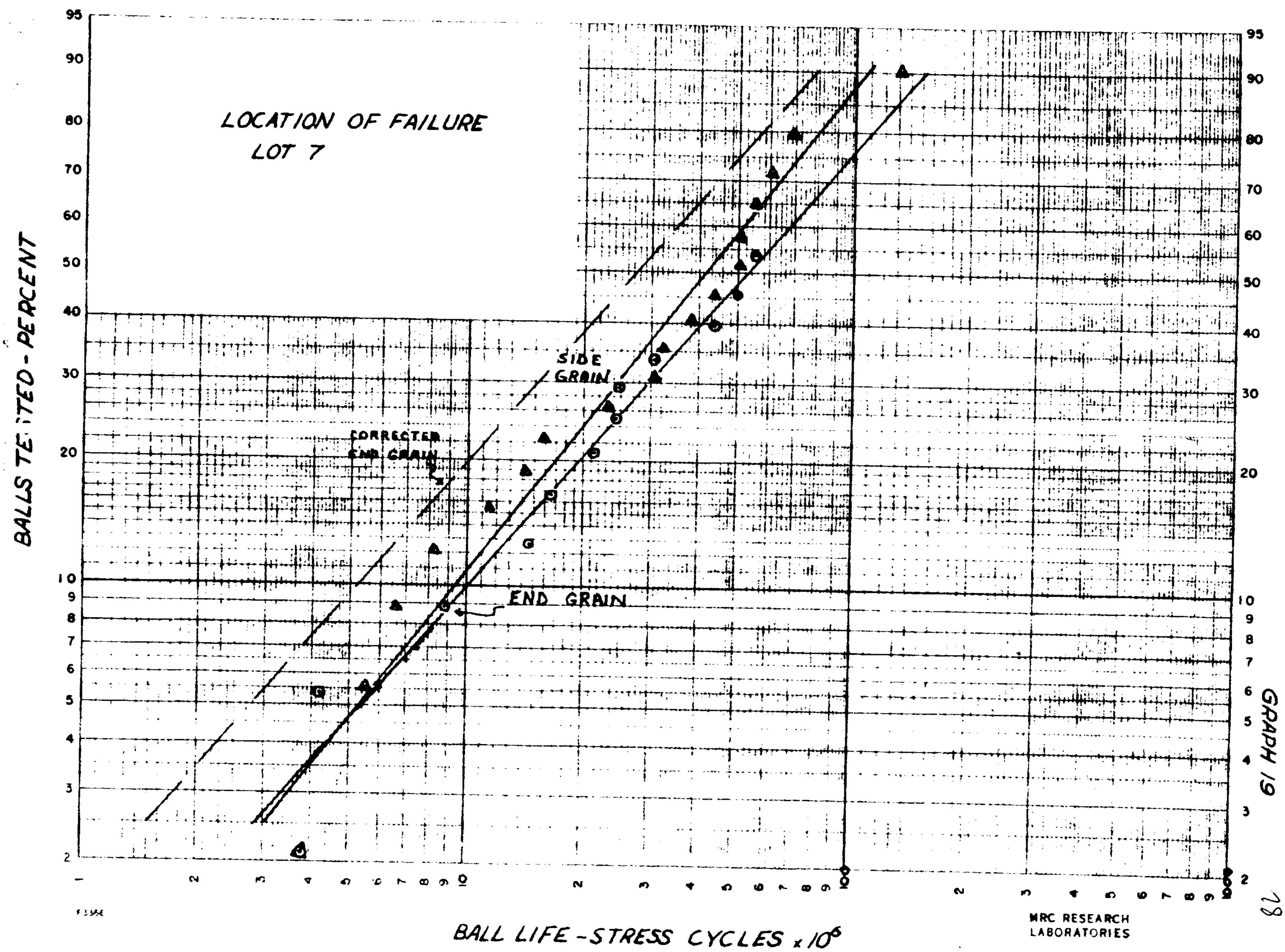
GRAPH 16


LOCATION OF FAILURE
LOT 5
END GRAIN
SIDE GRAIN
CORRECTED END GRAIN
BALLS TESTED - PERCENT
BALL LIFE - STRESS CYCLES x 10^6
MRC RESEARCH LABORATORIES


LOT No 5
LOCATION OF FAILURE
END FIBER
MEAN
MEDIAN
SIDE FIBER
MEDIAN
MEAN
80
70
60
50
40
30
20
10
0
BAL.S

GRAPH 18


LOT No. 7
LOCATION OF FAILURE
HOURS
10
20
30
40
50
60
70
80
90
100
END FIBER
MEAN
MEDIAN
SIDE FIBER
MEAN
MEDIAN
BALLS



GRAPH 19
LOCATION OF FAILURE
LOT 7
SIDE GRAIN
END GRAIN
CORRECTED END GRAIN
BALLS TESTED - PERCENT
BALL LIFE - STRESS CYCLES x 10^6
MRC RESEARCH LABORATORIES

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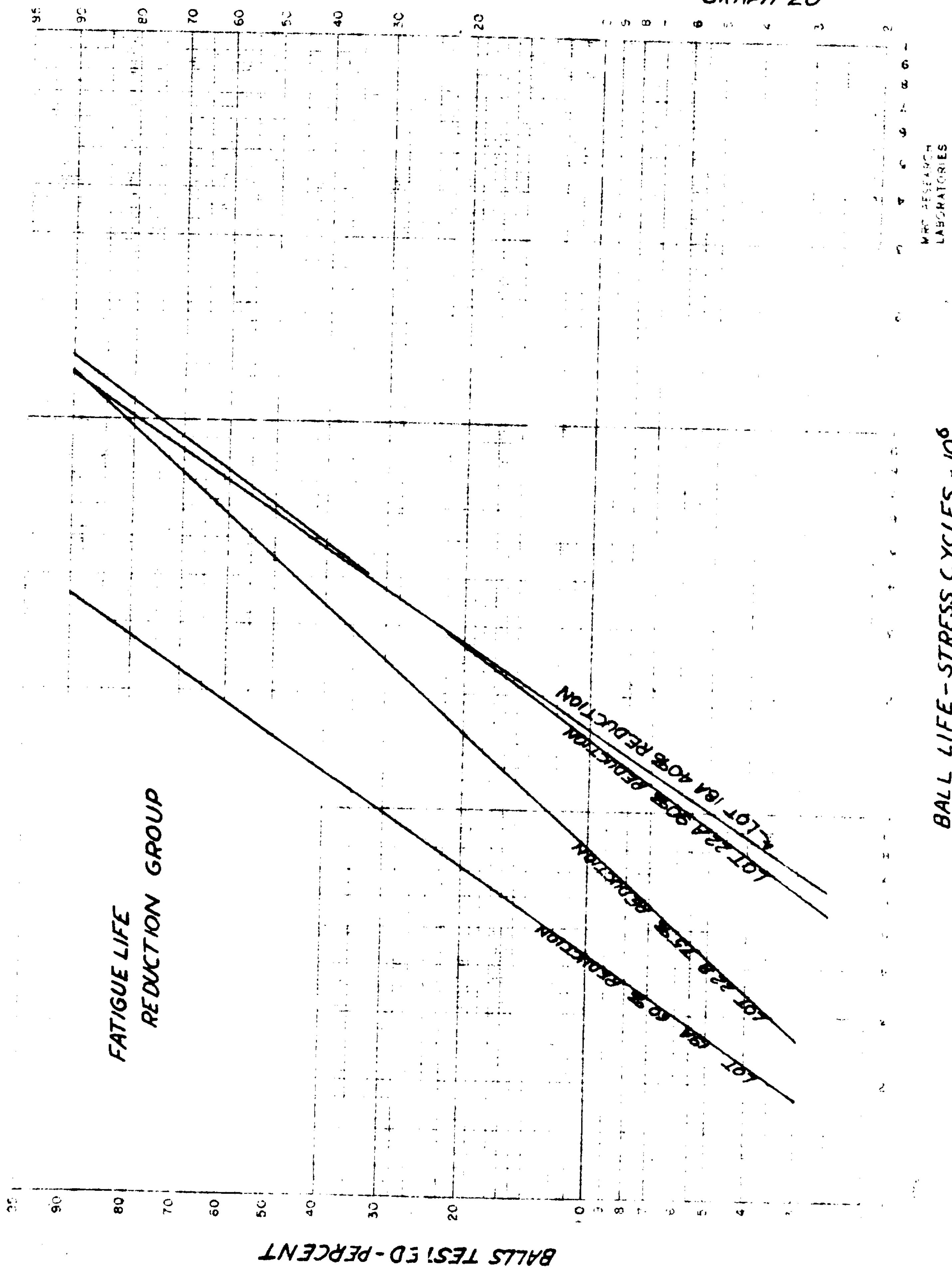
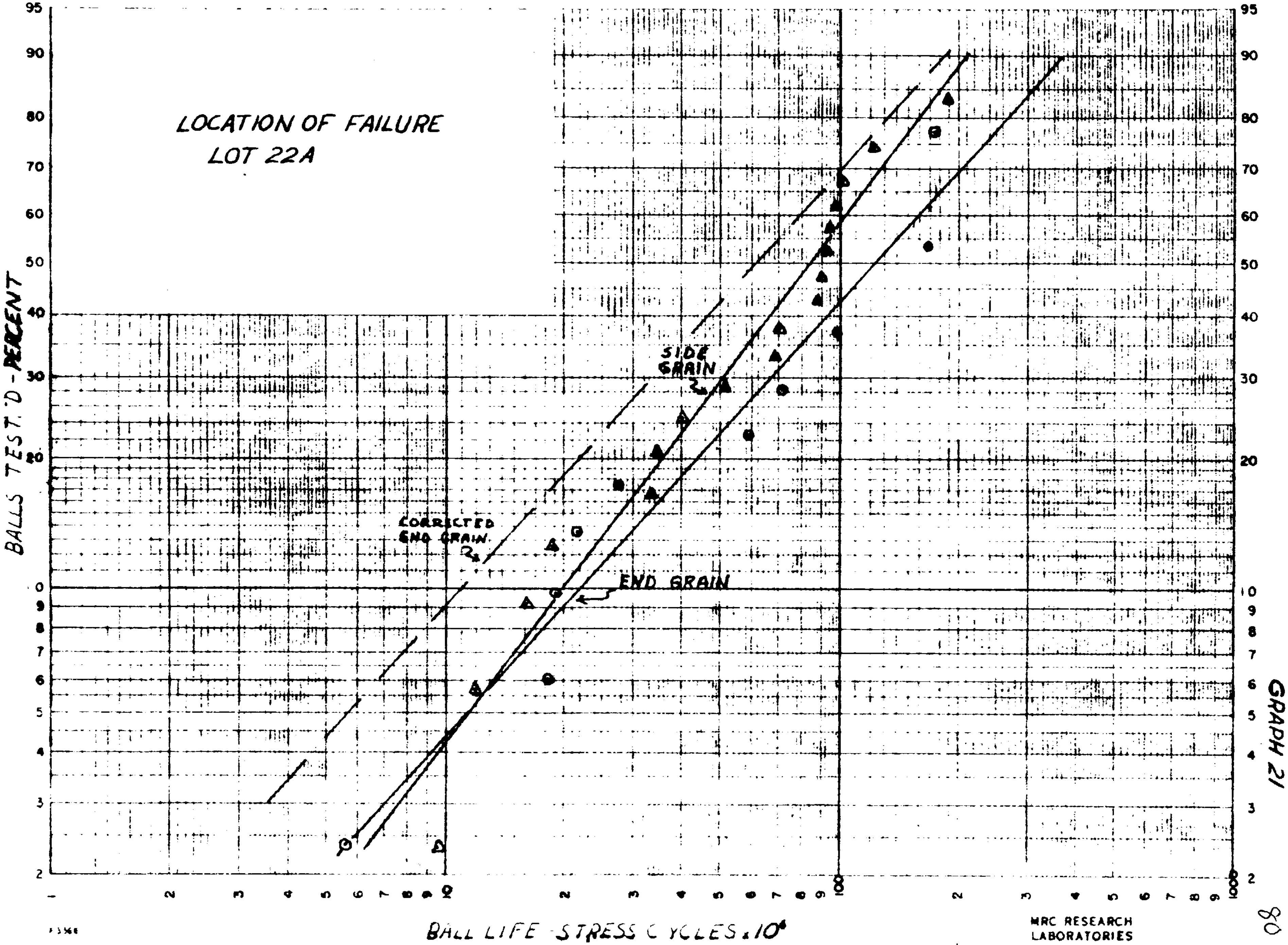
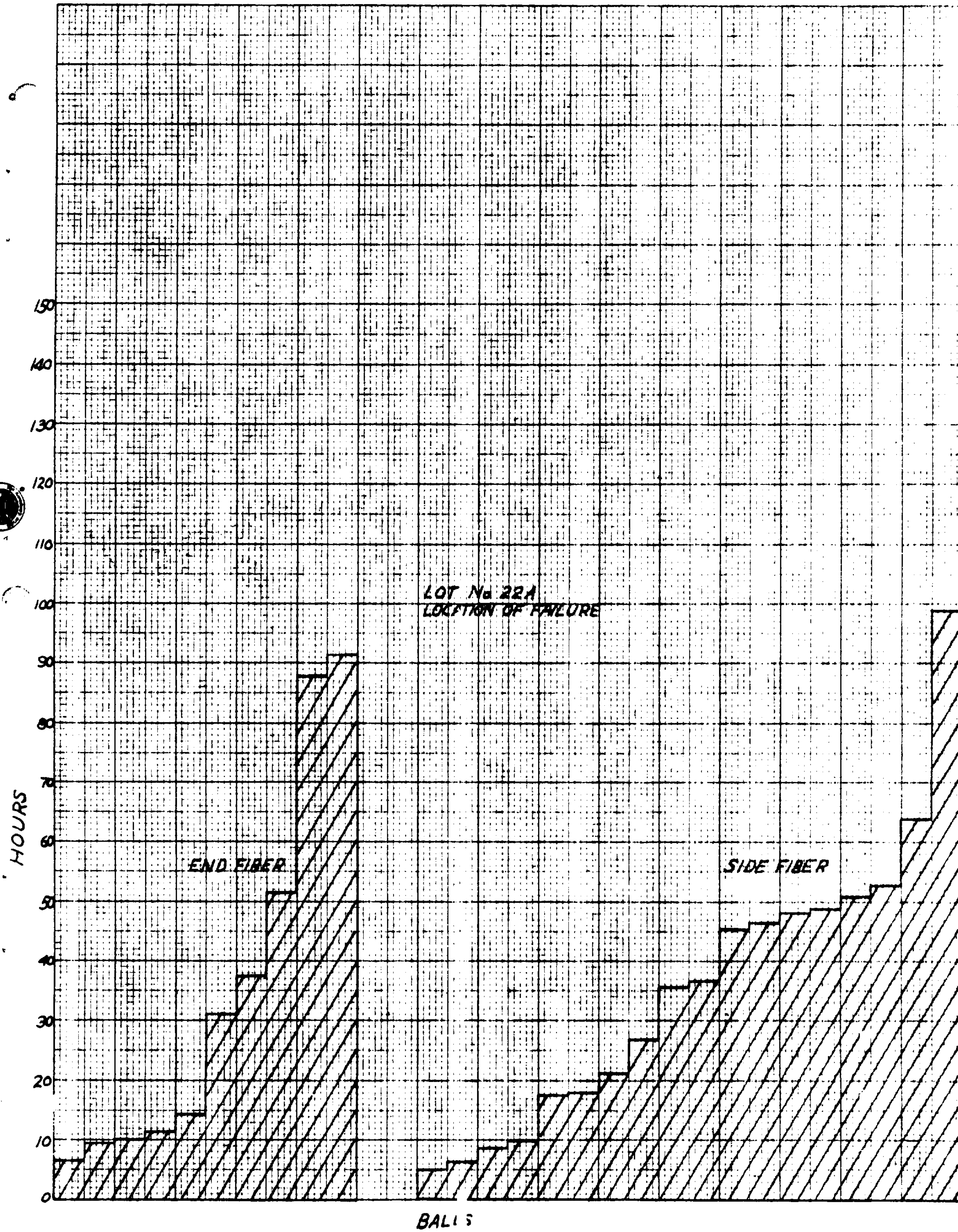
GRAPH 20

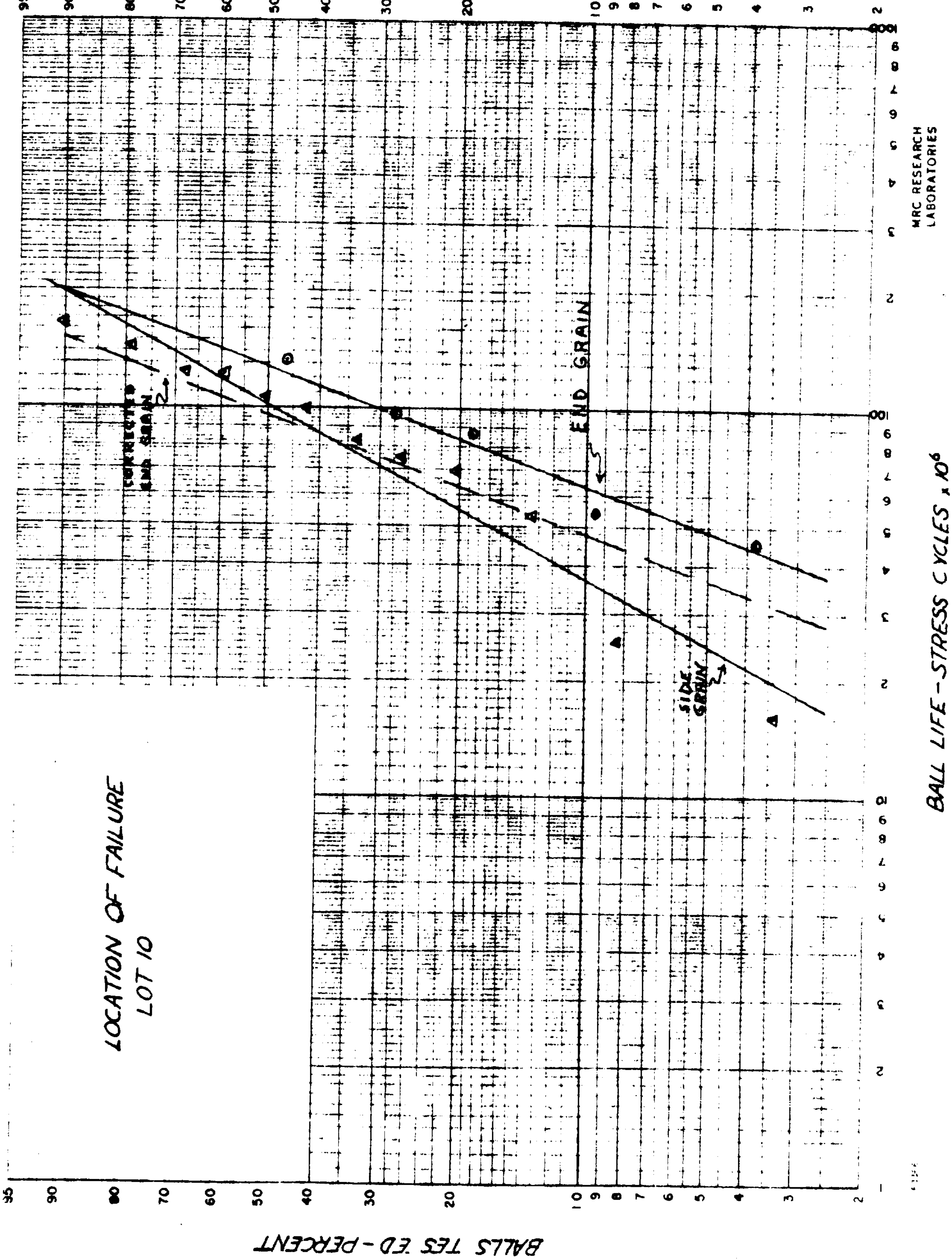

FATIGUE LIFE
REDUCTION GROUP
LOT 18A 40% REDUCTION
LOT 22A 30% REDUCTION
LOT 22B 75% REDUCTION
LOT 19A 60% REDUCTION
BALL LIFE-STRESS CYCLES x 10^6
BALLS TESTED-PERCENT

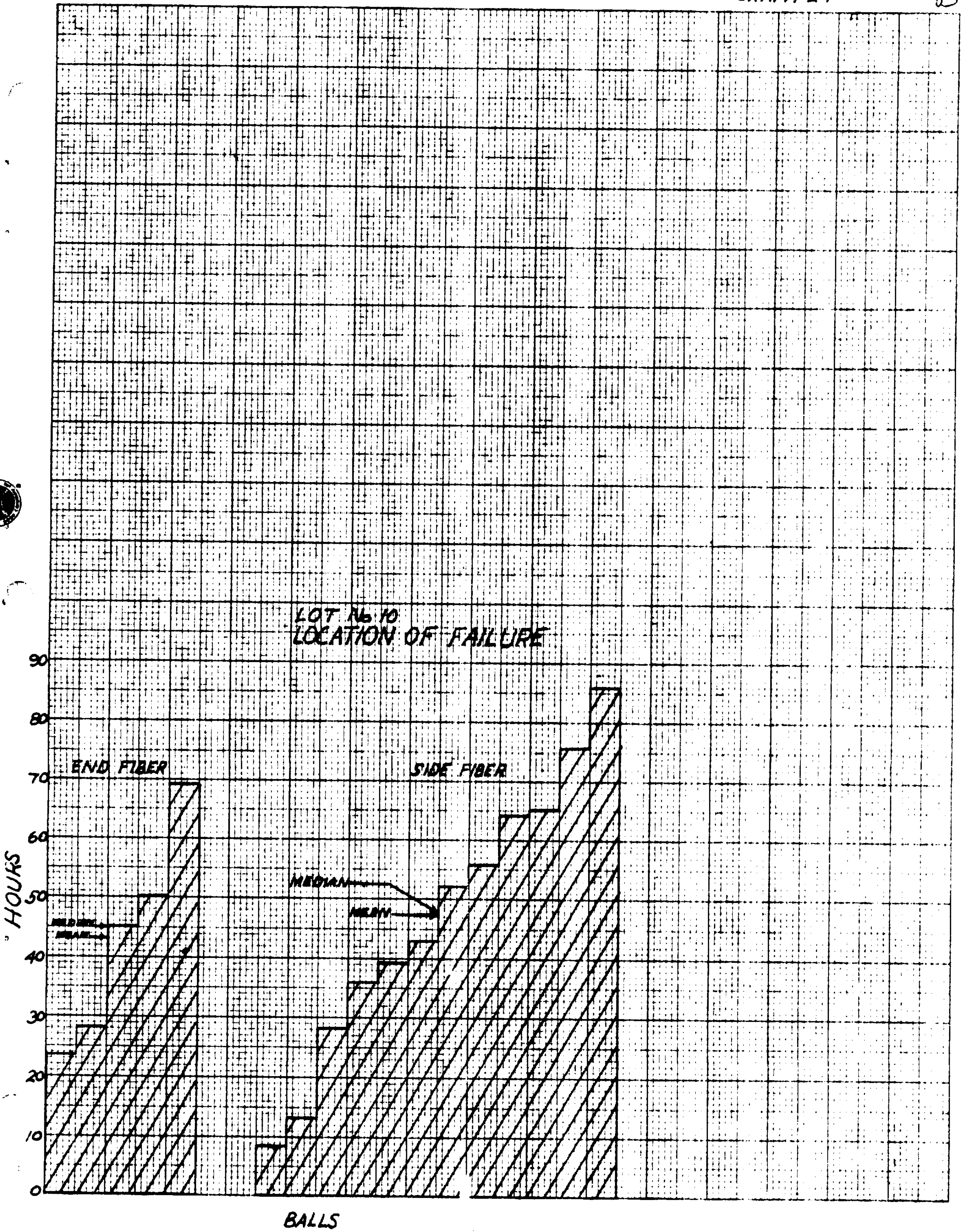


GRAPH 21
LOCATION OF FAILURE
LOT 22A
SIDE GRAIN
CORRECTED END GRAIN
END GRAIN
BALLS TEST'D - PERCENT
BALL LIFE - STRESS CYCLES x 10⁴
MRC RESEARCH LABORATORIES

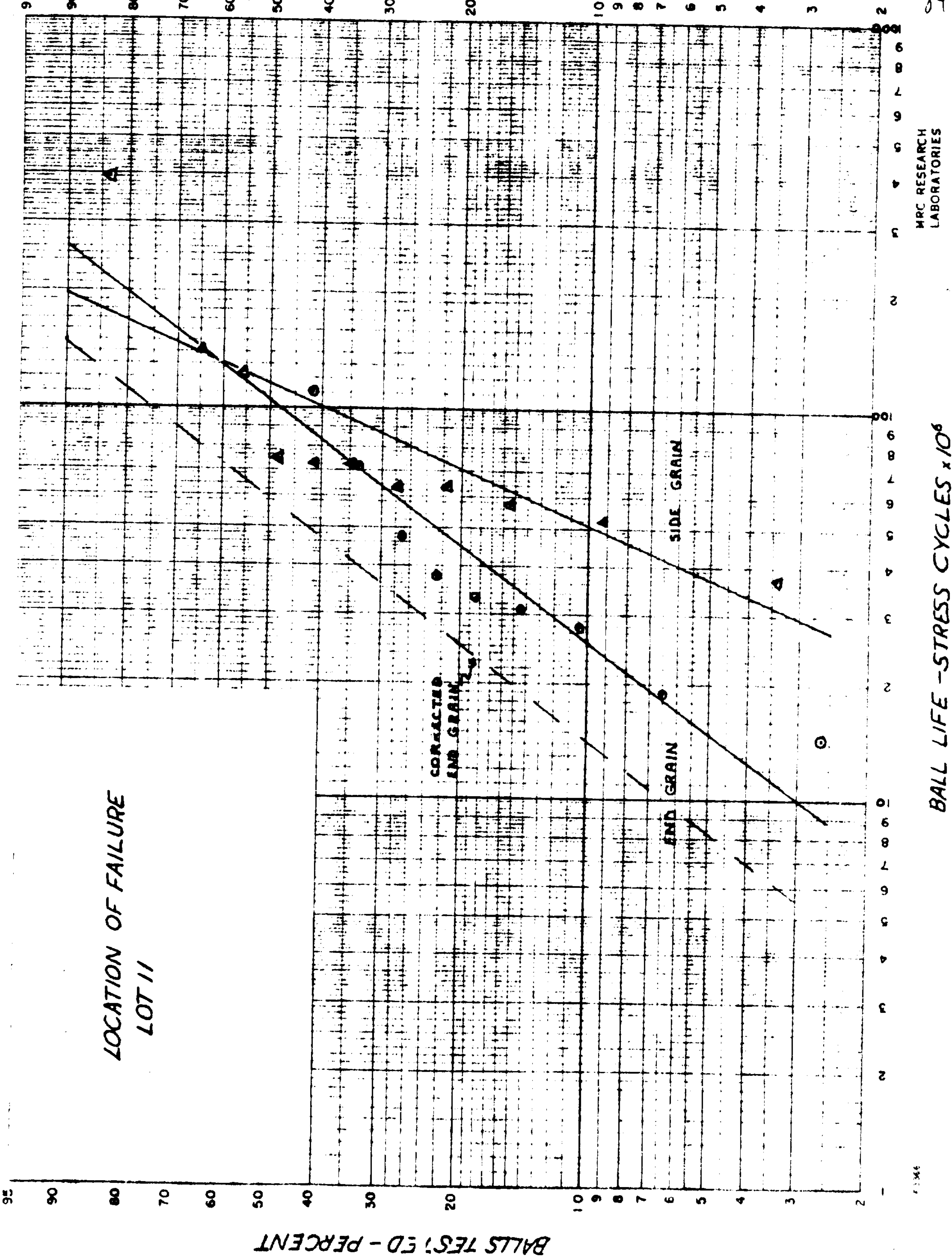
80


LOT No 22A
LOCATION OF FAILURE
HOURS
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
END FIBER
SIDE FIBER
BALLS

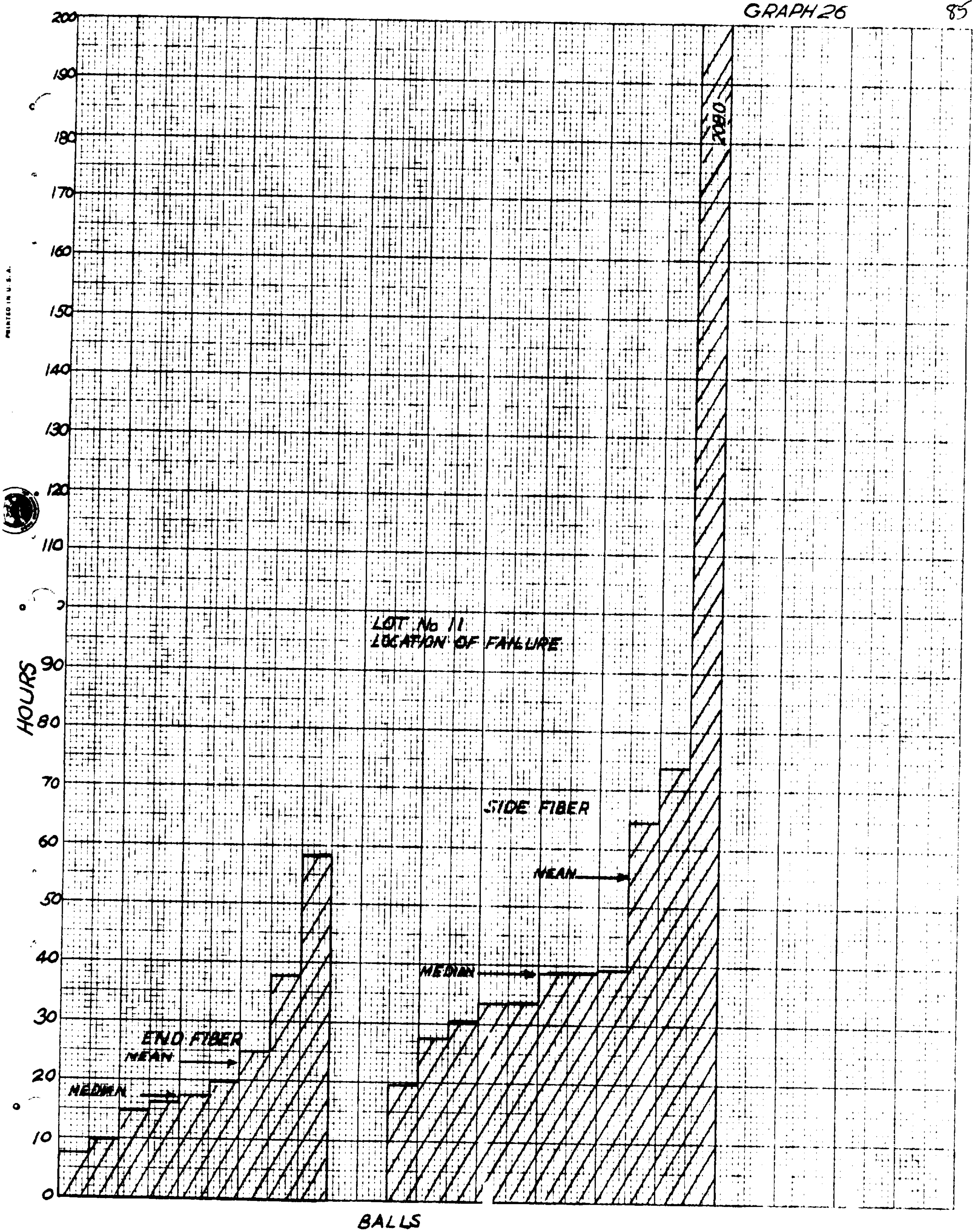

LOCATION OF FAILURE
LOT 10
CORRECTED END GRAIN
END GRAIN
SIDE GRAIN
BALL LIFE - STRESS CYCLES x 10^6
BALLS TESTED - PERCENT
MRC RESEARCH LABORATORIES


LOT No 10
LOCATION OF FAILURE
END FIBER
SIDE FIBER
MEDIAN
MEAN
HOURS
BALLS
0
10
20
30
40
50
60
70
80
90

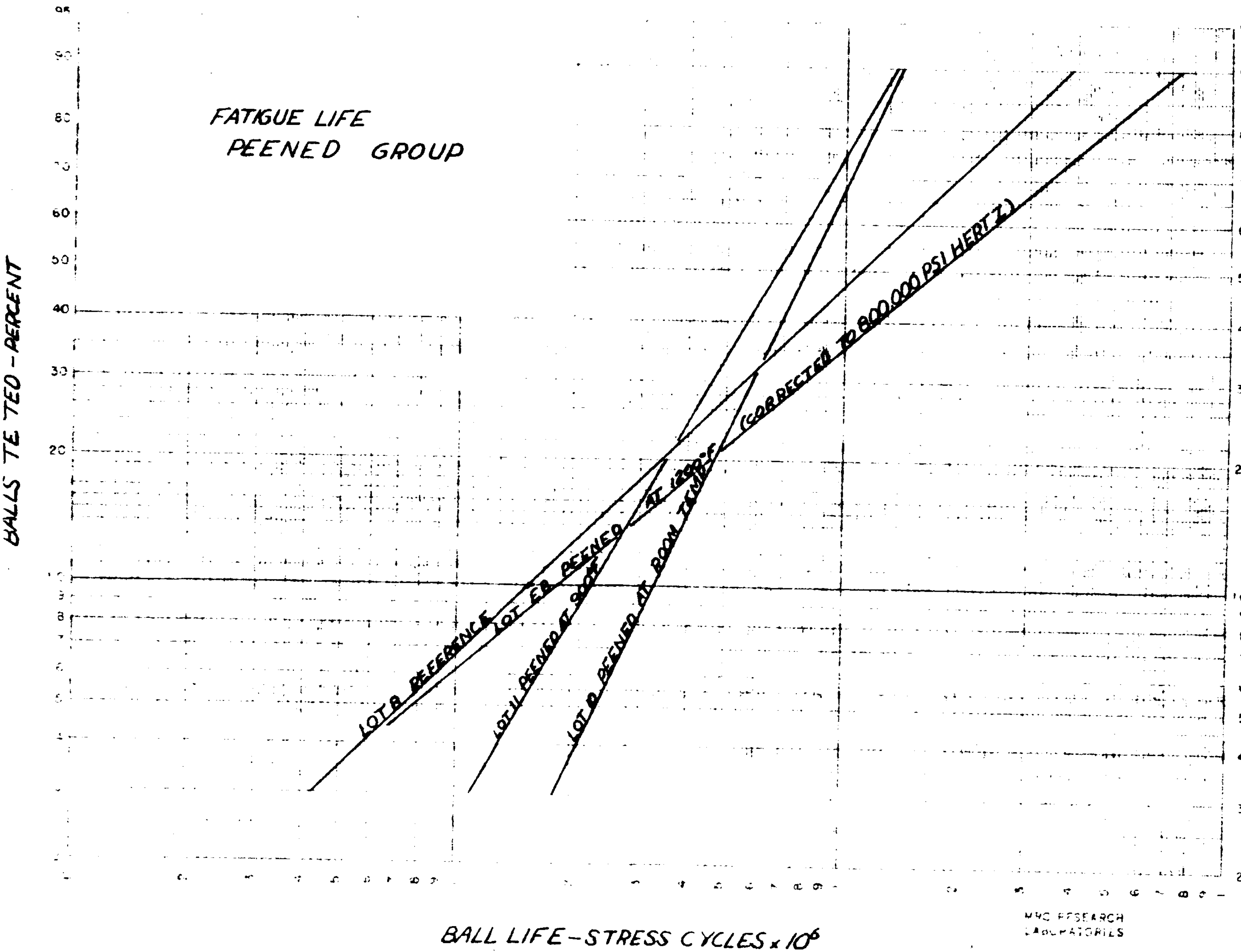
GRAPH 25


LOCATION OF FAILURE
LOT 11
BALL LIFE -STRESS CYCLES x10^6
BALLS TESTED - PERCENT
SIDE GRAIN
END GRAIN
CORRECTED END GRAIN
MRC RESEARCH LABORATORIES

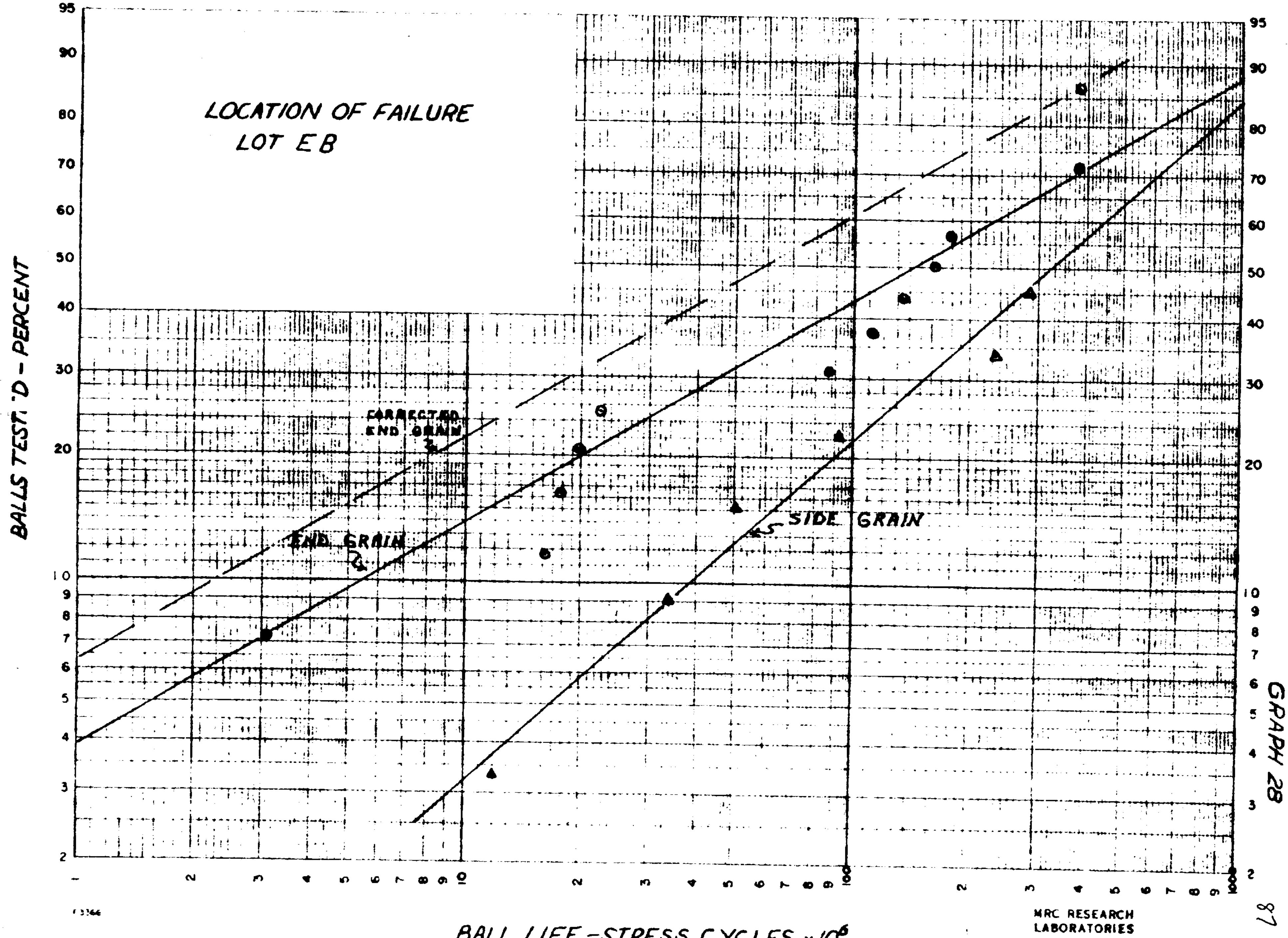
GRAPH 26

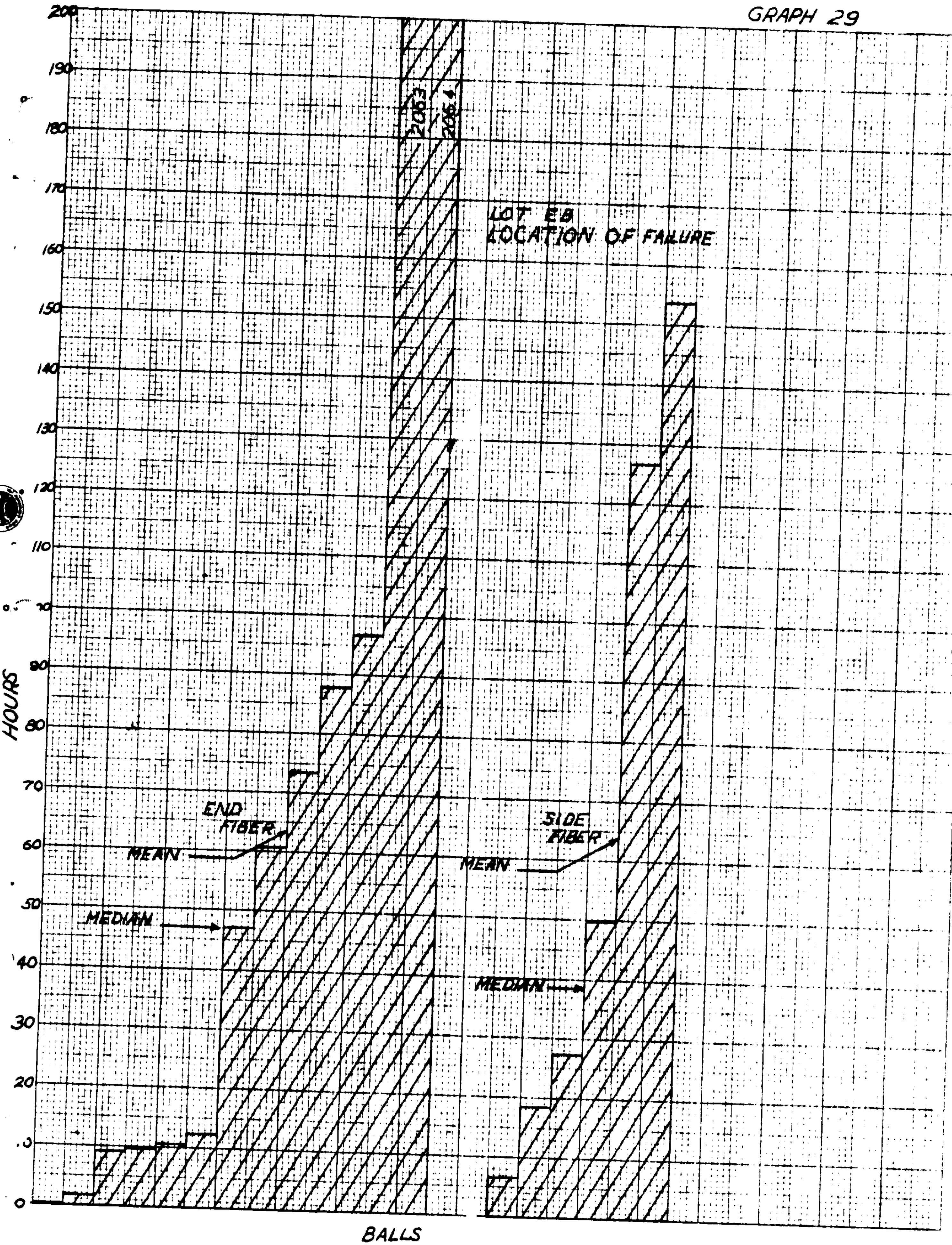

200
190
180
170
160
150
140
130
120
110
90
80
70
60
50
40
30
20
10
0
HOURS
BALLS
LOT No 11
LOCATION OF FAILURE
END FIBER
MEAN
MEDIAN
SIDE FIBER
MEAN
MEDIAN
2080

GRAPH 27

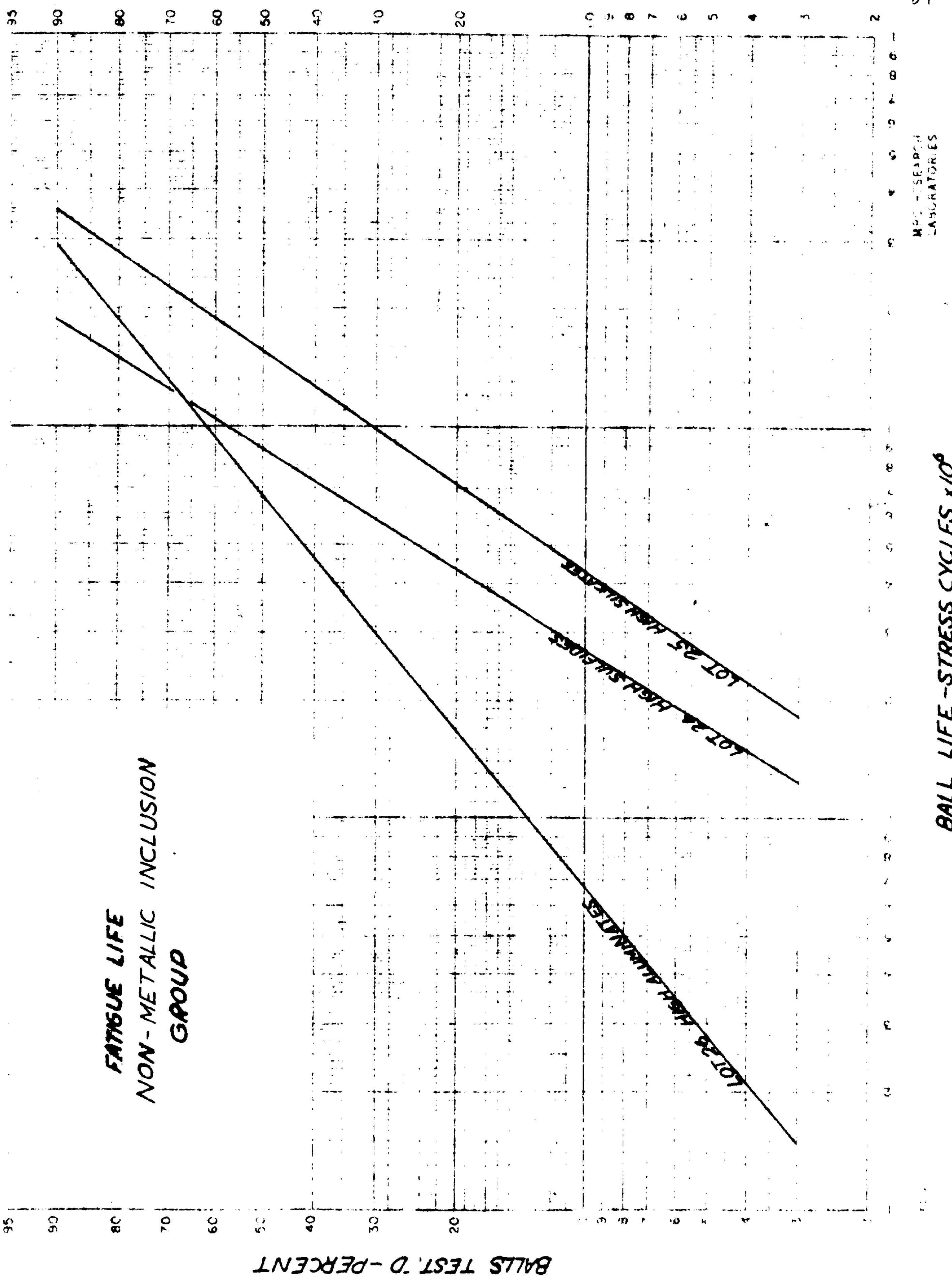


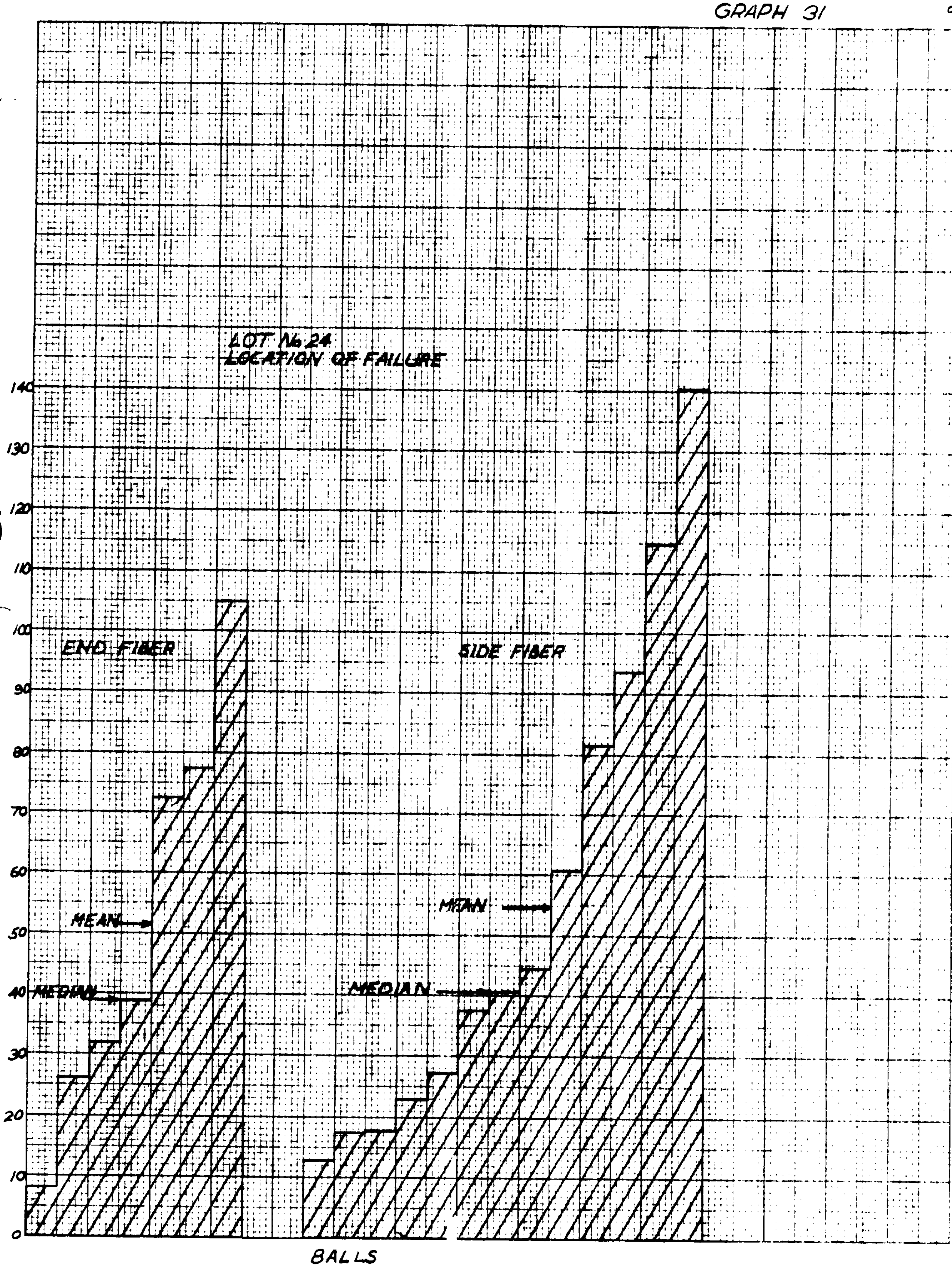
FATIGUE LIFE
PEENED GROUP
LOT B REFERENCE
LOT EB PEENED AT 1200°F
LOT 11 PEENED AT 900°F
LOT B PEENED AT ROOM TEMP.
(CORRECTED TO 800,000 PSI HERTZ)
BALLS TE TED - PERCENT
BALL LIFE - STRESS CYCLES x 10^6
95
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
MRC RESEARCH LABORATORIES


GRAPH 28
LOCATION OF FAILURE
LOT EB
CORRECTED END GRAIN
END GRAIN
SIDE GRAIN
BALLS TEST. 'D - PERCENT
BALL LIFE - STRESS CYCLES x 10^6
MRC RESEARCH LABORATORIES


GRAPH 29
LOT EB
LOCATION OF FAILURE
HOURS
BALLS
END FIBER
SIDE FIBER
MEAN
MEDIAN
206.3
206.4
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
PRINTED IN U.S.A.

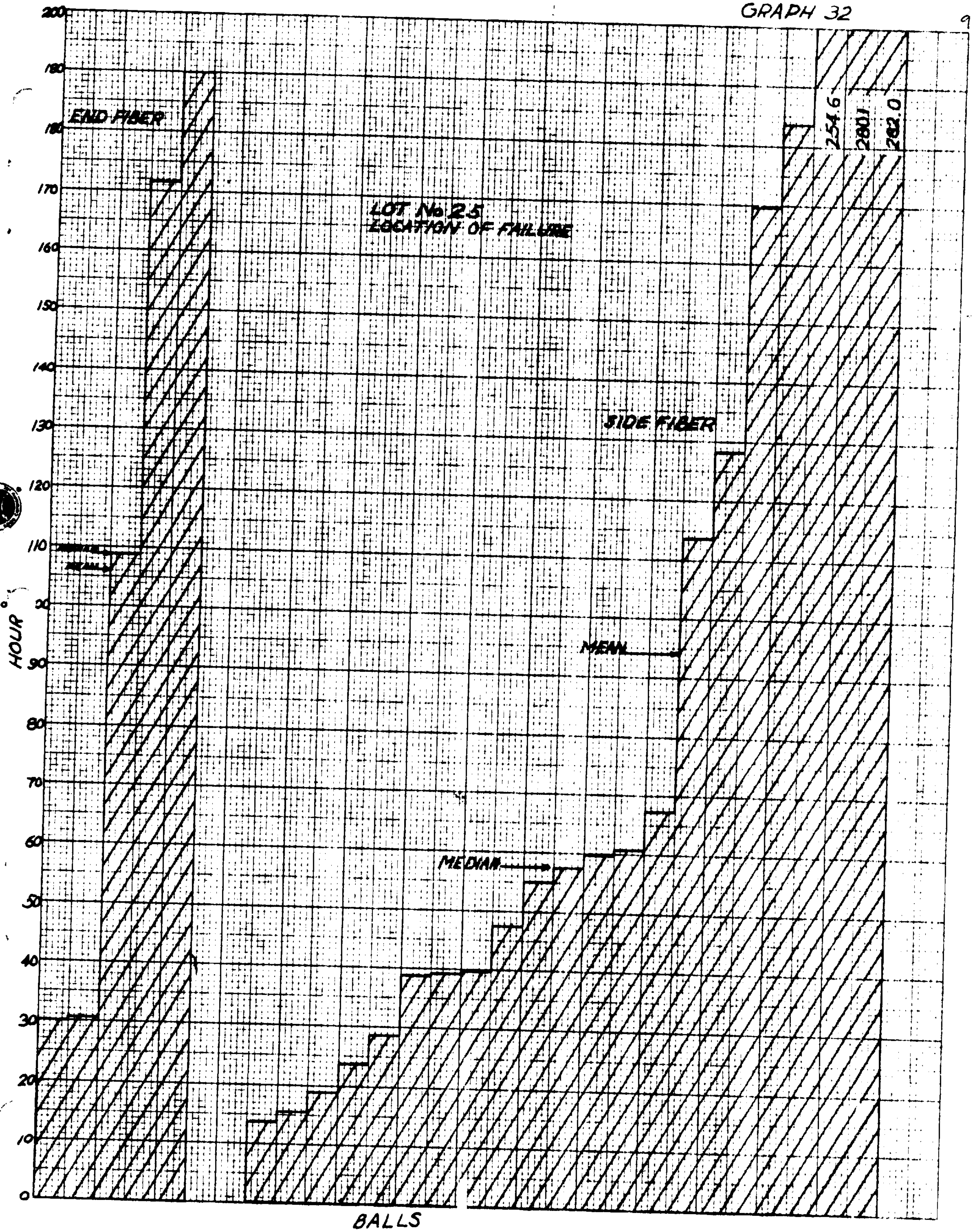
GRAPH 30

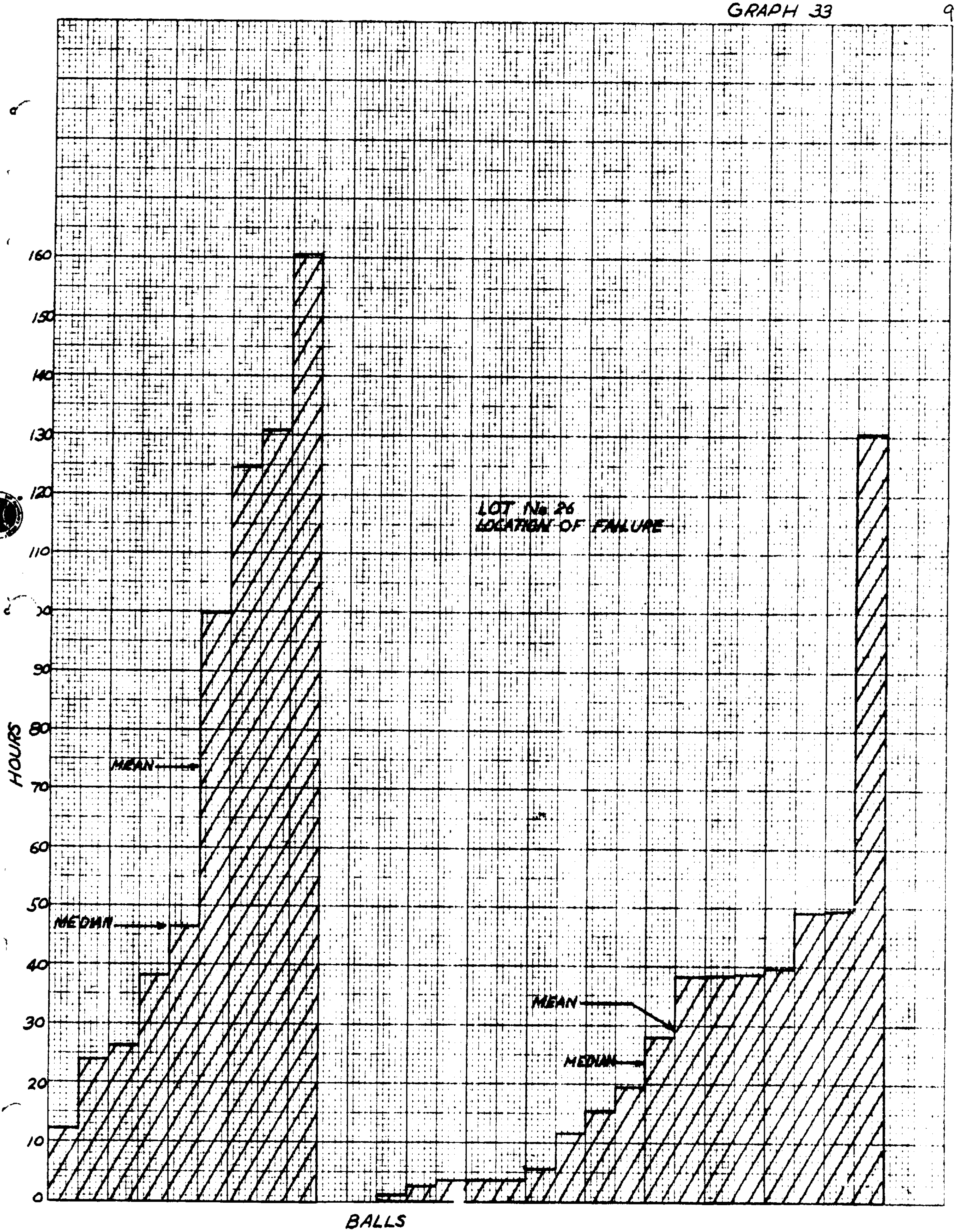

FATIGUE LIFE
NON-METALLIC INCLUSION
GROUP
LOT 25 HIGH SULFATES
LOT 24 HIGH SULFIDES
LOT 26 HIGH ALUMINATES
BALL LIFE-STRESS CYCLES x10^6
BALLS TEST'D-PERCENT



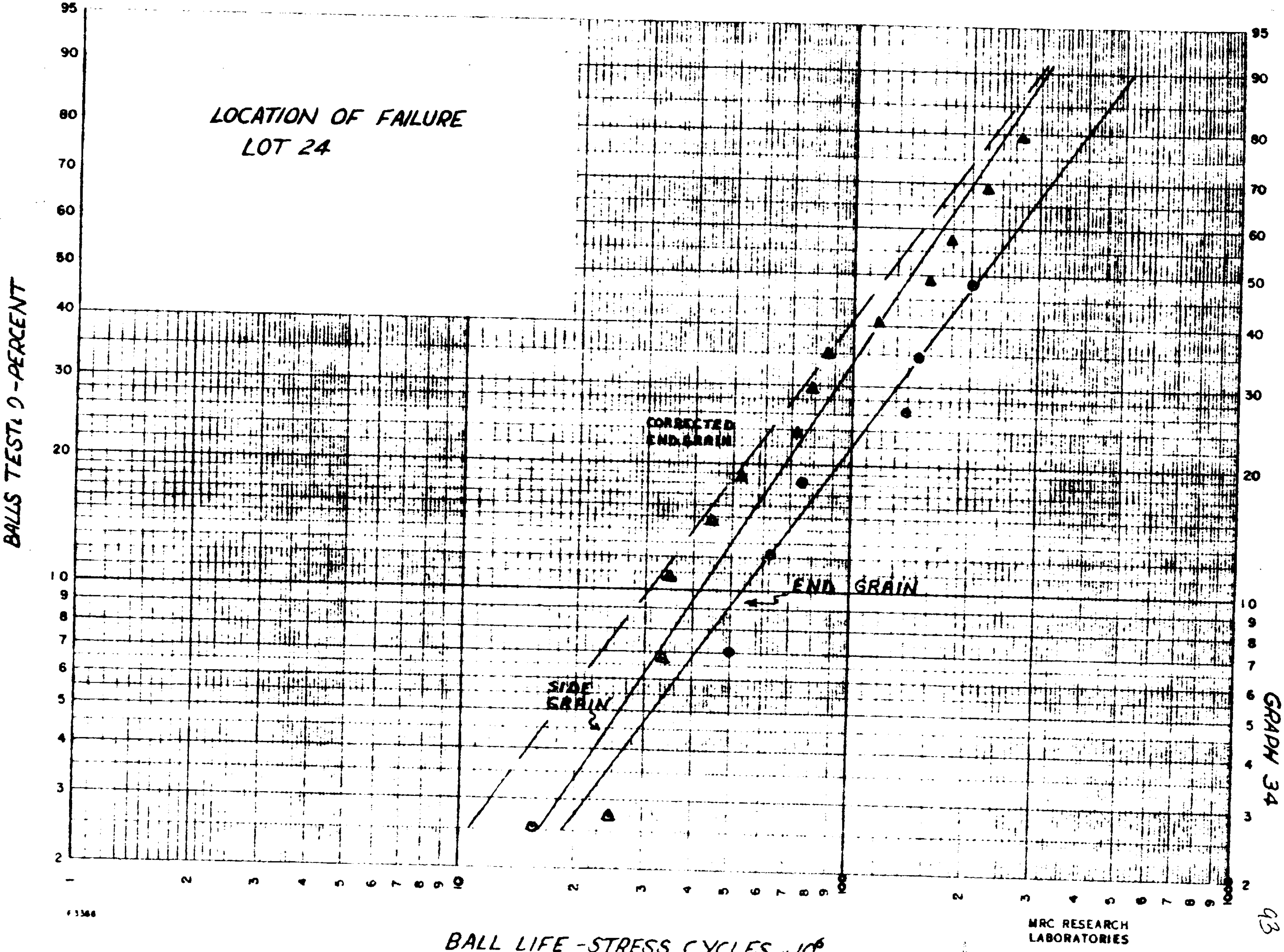
LOT No 24
LOCATION OF FAILURE
END FIBER
SIDE FIBER
MEAN
MEDIAN
MEAN
MEDIAN
HOURS
BALLS
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140

GRAPH 32

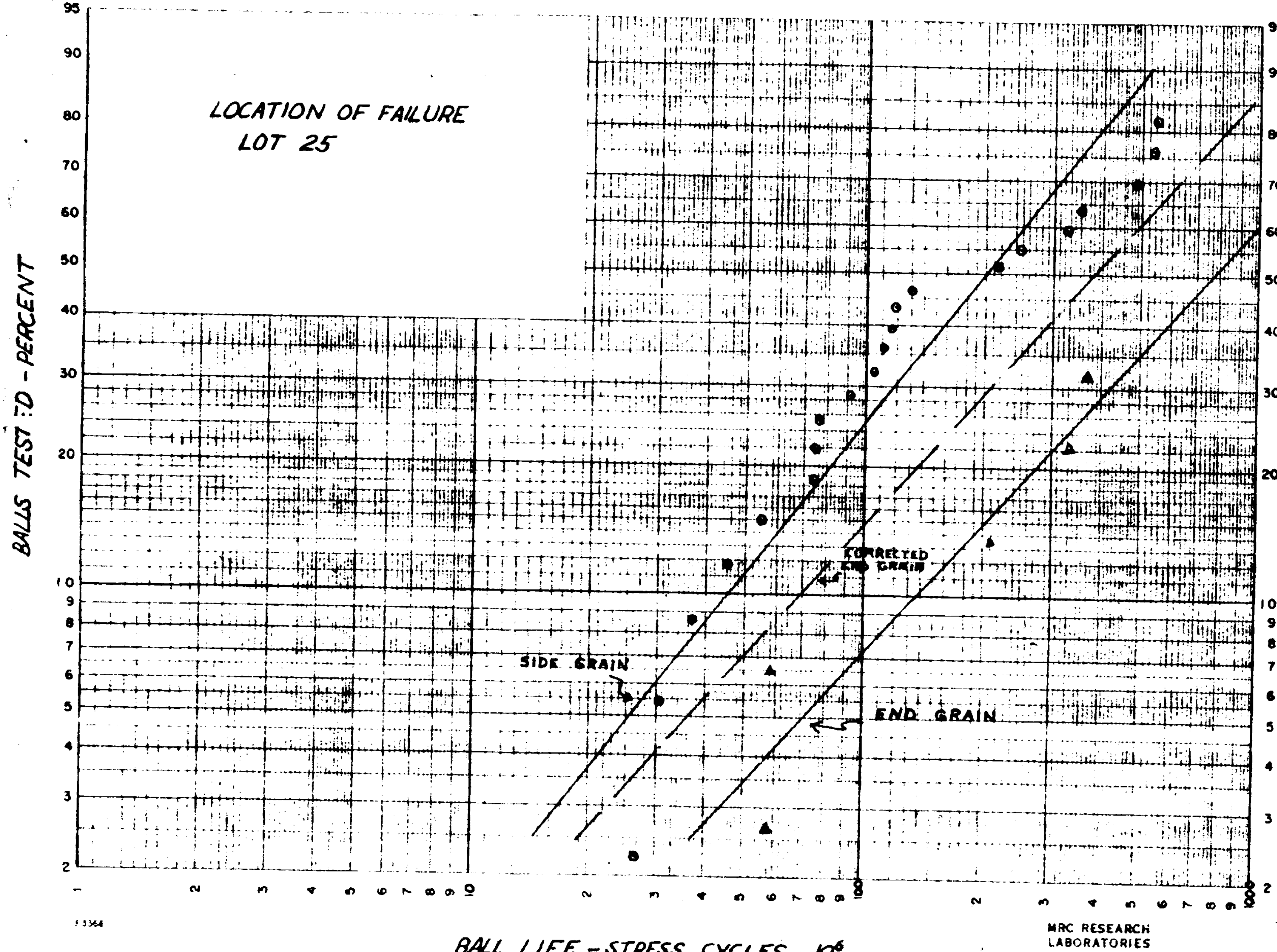

LOT No 25
LOCATION OF FAILURE
END FIBER
SIDE FIBER
MEDIAN
MEAN
254.6
280.1
282.0
HOUR
BALLS
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200


LOT No. 26
LOCATION OF FAILURE
HOURS
BALLS
MEAN
MEDIAN
MEAN
MEDIAN
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160

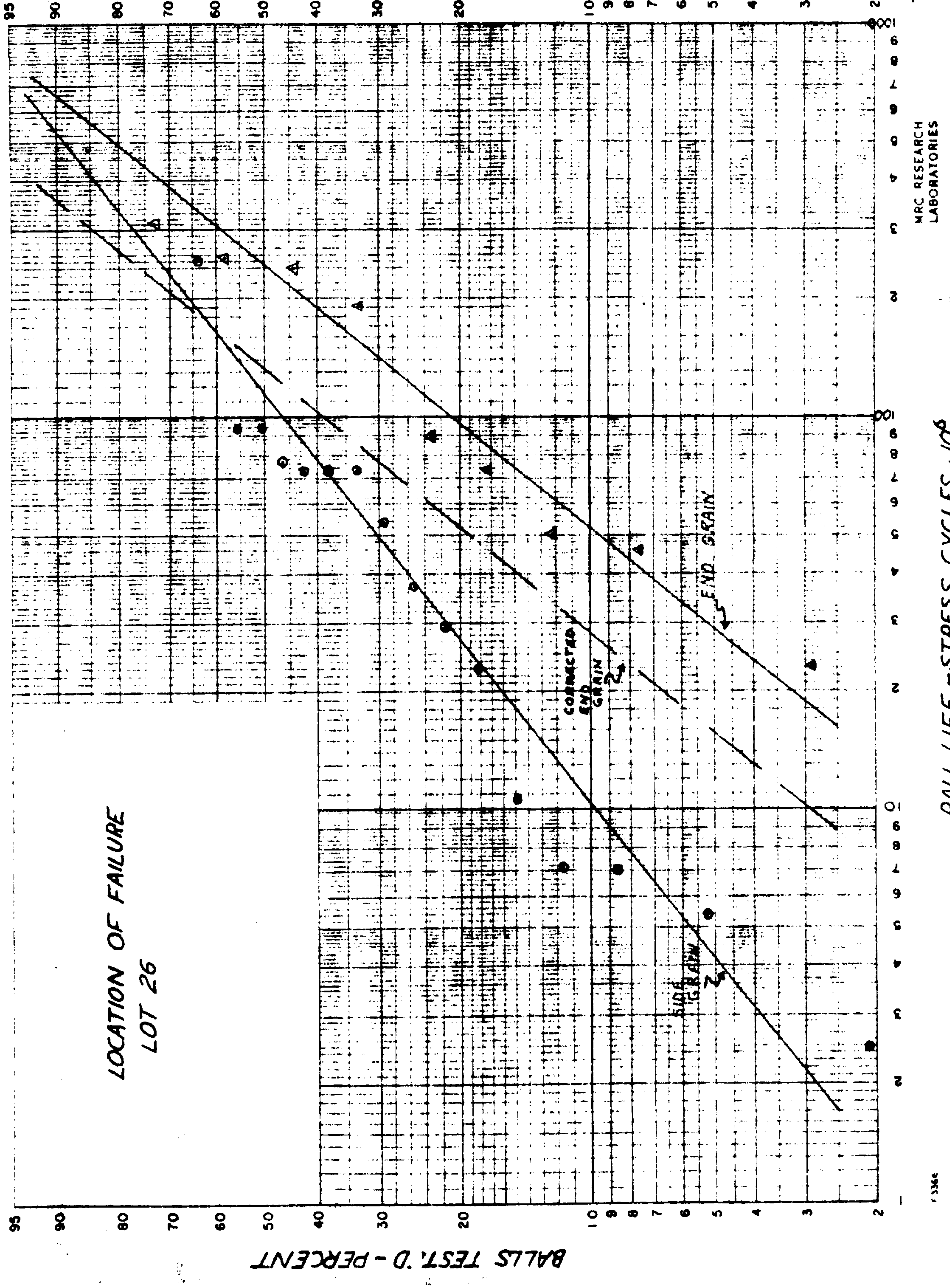
GRAPH 34


LOCATION OF FAILURE
LOT 24
CORRECTED END GRAIN
END GRAIN
SIDE GRAIN
BALLS TESTED-PERCENT
BALL LIFE-STRESS CYCLES x 10^6
MRC RESEARCH LABORATORIES

GRAPH 35

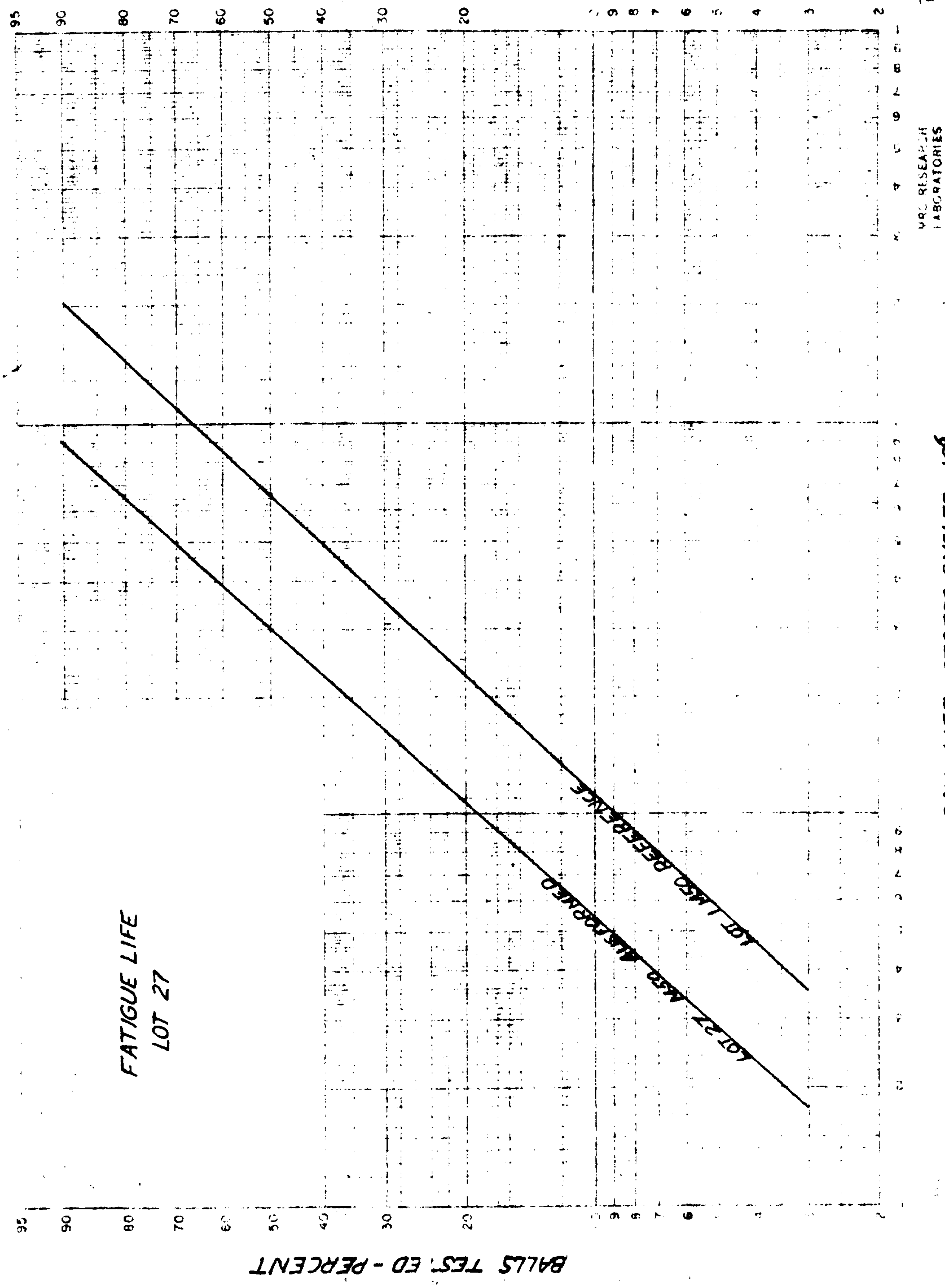

LOCATION OF FAILURE
LOT 25
BALLS TESTED - PERCENT
BALL LIFE - STRESS CYCLES x 10^6
SIDE GRAIN
END GRAIN
CORRECTED END GRAIN
MRC RESEARCH LABORATORIES

GRAPH 36


LOCATION OF FAILURE
LOT 26
BALLS TEST, D - PERCENT
BALL LIFE - STRESS CYCLES x 10^6
END GRAIN
CORRECTED END GRAIN
SIDE GRAIN
MRC RESEARCH LABORATORIES

GRAPH 37

96


FATIGUE LIFE
LOT 27
BALLS TESTED - PERCENT
LOT 1MSD REFERENCE
MRC RESEARCH LABORATORIES